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*Pacific University*

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# PASAT performance improves across adolescence in a sex-specific manner

## Abstract

**BACKGROUND:** The Paced Auditory Serial Addition Test (PASAT) is a sensitive measure of speed of information processing, sustained attention, and working memory. Notably, many of these cognitive processes develop across adolescence. Since much of the research has used the PASAT with adult populations, its effectiveness in assessing adolescent cognitive maturation remains unclear. In the current study, I examined several predictor variables of PASAT performance in a large sample of typically developing adolescents. Broadly, the aim of the current study was to investigate the development of executive functions across adolescence in order to enhance our understanding of brain behavior relationships during this important developmental period. More specifically, I wanted to assess the relationship between age and executive functioning by looking at performance on a sensitive measure of executive functioning, the PASAT, in an adolescent population. In the current study, I examined several predictor variables (age, sex, and IQ) of PASAT performance. **METHOD:** 101 adolescent boys and girls, ages 10 to 16 years ( $M = 13.1$ ,  $SD = 1.7$ ), completed a modified version of the PASAT that included 3.0 second (s) and 2.0s trials. Independent stepwise multiple regression analyses were conducted to determine the extent to which age, IQ, and gender predicted accuracy in performance on both trials of the PASAT in adolescents. **RESULTS:** Regression results indicated that the linear combination of age, IQ, and sex significantly predicted performance on the PASAT 3.0s. Age was the strongest predictor of PASAT 3.0s performance, with an increase in performance seen across adolescence. A significant positive relationship was also seen between PASAT 3.0s performance and IQ. Lastly, sex also was a significant predictor, with boys performing significantly better than girls. Similar results were seen when examining the influence of age, IQ, and sex on PASAT 2.0s performance. **CONCLUSIONS:** Overall, these results show performance on a modified adult version of the PASAT improves across adolescence, and that IQ and sex are also contributory. These findings suggest that the adult version of the PASAT is an appropriate and sensitive measure to capture the development of higher-order cognitive processes during adolescence.

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Dissertation

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PASAT PERFORMANCE IMPROVES ACROSS ADOLESCENCE IN A SEX-  
SPECIFIC MANNER

A DISSERTATION  
SUBMITTED TO THE FACULTY  
OF  
SCHOOL OF PROFESSIONAL PSYCHOLOGY  
PACIFIC UNIVERSITY  
HILLSBORO, OREGON

BY  
JILL S. WALDMAN  
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## ABSTRACT

**BACKGROUND:** The Paced Auditory Serial Addition Test (PASAT) is a sensitive measure of speed of information processing, sustained attention, and working memory. Notably, many of these cognitive processes develop across adolescence. Since much of the research has used the PASAT with adult populations, its effectiveness in assessing adolescent cognitive maturation remains unclear. In the current study, I examined several predictor variables of PASAT performance in a large sample of typically developing adolescents. Broadly, the aim of the current study was to investigate the development of executive functions across adolescence in order to enhance our understanding of brain behavior relationships during this important developmental period. More specifically, I wanted to assess the relationship between age and executive functioning by looking at performance on a sensitive measure of executive functioning, the PASAT, in an adolescent population. In the current study, I examined several predictor variables (age, sex, and IQ) of PASAT performance. **METHOD:** 101 adolescent boys and girls, ages 10 to 16 years ( $M = 13.1$ ,  $SD = 1.7$ ), completed a modified version of the PASAT that included 3.0 second (s) and 2.0s trials. Independent stepwise multiple regression analyses were conducted to determine the extent to which age, IQ, and gender predicted accuracy in performance on both trials of the PASAT in adolescents. **RESULTS:** Regression results indicated that the linear combination of age, IQ, and sex significantly predicted performance on the PASAT 3.0s. Age was the strongest predictor of PASAT 3.0s performance, with an increase in performance seen across adolescence. A significant positive relationship was also seen between PASAT 3.0s performance and IQ. Lastly, sex also was a significant predictor, with boys performing significantly better than girls.

Similar results were seen when examining the influence of age, IQ, and sex on PASAT 2.0s performance. **CONCLUSIONS:** Overall, these results show performance on a modified adult version of the PASAT improves across adolescence, and that IQ and sex are also contributory. These findings suggest that the adult version of the PASAT is an appropriate and sensitive measure to capture the development of higher-order cognitive processes during adolescence.

Key Words: PASAT, adolescence, executive functioning, cognitive development, intelligence, age, sex.

## TABLE OF CONTENTS

	Page
ABSTRACT.....	i
LIST OF TABLES.....	v
INTRODUCTION .....	2
Typical Brain Development.....	4
Gray Matter Development .....	6
White Matter Development.....	8
Sex-Based Differences in Brain Development .....	10
Executive Functions.....	14
Cognitive and Executive Functions Develop Across Adolescence .....	15
Attention .....	18
Working Memory.....	20
Response Inhibition .....	25
Processing Speed .....	27
Integration of Executive Functions.....	29
Sex Based Differences in Cognitive Functioning.....	30
The PASAT.....	31
PASAT and Age .....	34
PASAT and Intellectual Ability.....	35
PASAT and Education .....	36
PASAT and Gender .....	36
PASAT and Ethnicity .....	37

PASAT and Math Performance .....	37
Study Rationale .....	38
Research Questions .....	39
Hypotheses .....	39
METHOD .....	40
Participants and Setting .....	40
Materials and Procedure .....	41
Screening .....	42
Neuropsychological Screen .....	43
Measures .....	43
RESULTS .....	47
Pre-Analysis Data Screen .....	47
Multiple Regression Analyses .....	48
Follow Up Analyses .....	55
Interaction Effect for Age .....	55
Interaction Effect for IQ .....	58
DISCUSSION .....	61
Overview of Findings and Potential Implications .....	61
Limitations .....	80
REFERENCES .....	87



## LIST OF TABLES

Table	Page
Table 1: .....	46
Table 2: .....	50
Table 3: .....	50
Table 4: .....	52
Table 5: .....	54
Table 6: .....	56
Table 7: .....	56
Table 8: .....	57
Table 9: .....	59
Table 10: .....	59
Table 11: .....	60

## LIST OF FIGURES

Figure	Page
Figure 1: .....	53
Figure 2: .....	54

## INTRODUCTION

Adolescence is not strictly defined by age and varies considerably between individuals, due to the influence of puberty and sex-based differences (Dahl, 2004; Spear, 2000). Adolescence represents the major transition that takes place over most of the second decade of human life. It is the final phase of a prolonged pattern of growth and maturation, characterized by changes in physical growth, physiology, and cognitive and emotional skills (for review, see Paus, 2005). The interface between affect, reasoning and decision making, and action is of vital importance during adolescent development (for review, see Steinberg, 2005). Adolescence is characterized by brain-based vulnerabilities (Fischer, Biscaldi, & Gezeck, 1997; Kail 1993; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Munoz, Broughton, Goldring, & Armstrong, 1998) and pubertal changes (for review, see McEwen, 2001) that affect decision-making skills and behavior. Specifically, adolescence has been associated with the emergence of psychopathology (Chau, Roth, & Green, 2004; for reviews, see Everling & Fisher, 1998; Sweeney, Takarae, Macmillan, Luna, & Minshew, 2004), increases in risk taking behavior (Maggs, Almeida & Galambos, 1995) and important sex-based differences in cognitive and emotional functioning (Collins & Kimura, 1997; Delgado & Prieto, 1996).

Adolescence is often referred to as a vulnerable developmental period characterized by immature brain processes and limitations in planning, decision making, and the ability to voluntarily control behavior in a planned fashion, as compared with adults (e.g., Anderson, Anderson, & Garth, 2001; Casey et al., 1997; Reiss, Abrams, Singer, Ross, & Denckla, 1996; Sowell, Thompson, Tessner, & Toga, 2001; for reviews, see Dahl, 2004; Paus, 2005; Spear, 2000). Although gross morphology of the brain and

core cognitive abilities have developed by adolescence, significant refinements to brain processes continue into adulthood (Yakovlev & Lecours, 1967; Huttenlocher, 1990). In particular, there is protracted development of the prefrontal cortex, which continues to develop throughout adolescence and into adulthood (Barnea-Goraly et al., 2005, Giedd, 2004; Schmithorst, Wilke, Dardzinski, & Holland, 2002; for reviews see Giedd et al., 1999, Marsh, Gerber, & Peterson, 2008; Paus 2005). This refining process is thought to subserve the continuing development of cognitive control including many higher order cognitive functions, such as working memory, set shifting, behavioral inhibition, and decision making (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Braver & Barch, 2002; Demetriou, Christou, Spanoudis, & Platsidou, 2002; Goldman-Rakic & Leung, 2002; Huttenlocher, 1990; Levin, Culhane, Hartmann, Evankovich, & Mattson, 1991; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Marsh et al., 2006; For reviews, see Blakenore & Chowdry, 2006; Krawczyk, 2002). Information processing speed has also been shown to improve throughout childhood and adolescence (Elliott, 1970; Fischer, Biscaldi, & Gezeck, 1997; Fry & Hale, 1996; Fukushima, Hatta, & Fukushima, 2000; Hale, 1990; Kail, 1986; 1991; 1993; Munoz, Broughton, Goldring, & Armstrong, 1998).

The purpose of the present study is to investigate more closely the cognitive changes that occur during adolescence. By using a sensitive measure of executive functioning, the PASAT, I hope to capture the development of many of these higher order cognitive functions throughout this developmental period. Specifically, the PASAT has been shown to require the integration of many cognitive processes, including multiple attentional processes (sustained and selective attention), working memory, inhibition, and

processing speed (Audoin et al., 2003; Christodoulou et al., 2001; Cicerone, 1997; Cicerone & Azulay, 2002; Di Stefano & Radanov, 1995; Gronwall, 1986; Johnson, Roethig-Johnston, & Middleton, 1998; Litvan, Grafman, Vendrell, & Martinez, 1988; Snyder & Cappelleri, 2001; Spreen & Strauss, 1998; Webbe & Ochs, 2003). Although these are just a few of the many cognitive abilities that have been shown to improve during adolescence, they will be the four main functions I focus on throughout this dissertation. Before discussing literature on the cognitive and behavioral changes that take place across adolescence, I will first review the basic neurobiological processes that occur throughout childhood and adolescence, and which are thought to underlie many of these cognitive changes. Understanding the normative changes in hormonal functioning and brain structure that take place during this important developmental period is crucial to our understanding of cognitive and behavioral development. I will then review the literature on the development of many cognitive processes and executive functions during this developmental period, as well as discuss important sex-based differences in development that are prevalent at this time. Lastly, I will review the literature on the PASAT as a sensitive measure of executive functioning.

### **Typical Brain Development**

While post mortem studies have helped us understand the very basic cellular changes that occur over the lifespan, more recent technological advancements, including the advent of magnetic resonance imaging (MRI), have allowed us to safely explore both typical and pathological brain development across the human lifespan (for review, see Sowell, Thompson, & Toga, 2004). Not only does MRI provide accurate anatomical images of brain structures and allow us to study both structural and functional changes of

the human brain, *in vivo*, but it also gives us the opportunity to study individuals at multiple time points, thus capturing developmental effects, while controlling for inter-subject variability. Magnetic resonance imaging (MRI) has helped elucidate the relationship between cognitive and behavioral development during childhood and adolescence, and the maturation of specific neural networks that support these developments.

Development and growth of the human brain is most prominent during the first three years of life, and by the fifth year, brain weight has reached approximately 90% of adult values (Dekaban, 1978). During childhood and adolescence, changes in brain morphology are subtle, occurring at a much slower rate (Giedd et al., 1999; Jernigan, Trauner, Hesselink, & Tallal, 1991; Sowell, Trauner, Gamst, & Jernigan, 2002; for review, see Paus, Colins, Evans, Leonard, Pike, & Zijdenbos, 2000). However, this time is marked by extremely active cortical development characterized by rapid synaptogenesis and myelination (Dobbing & Sands, 1973). Early developmental synaptogenesis is thought to result in an overproduction of synapses relative to those needed in the adult state (Huttenlocher, 1979). Myelination occurs as oligodendrocytes generate a fatty-lipid insulation (myelin) that covers neuronal axons. This myelin coating increases the propagation of electrical signals, which optimizes the transfer of information throughout widely distributed circuits in the central nervous system (Changeux & Danchin, 1976; Huttenlocher, 1979; Yakovlev & Lecours, 1967).

Up to the age of five, cerebral volume continues to increase in cortical gray and white matter volumes of up to 1-mm per year (Dobbing & Sands, 1973; Huttenlocher & Dabholkar, 1997; Matsuzawa et al., 2001; for review, see Sowell et al., 2004). At this

time, total brain volume becomes relatively stable and a refining process of existing neural processes begins (Goldman-Rakic, 1987). This refining process continues throughout childhood, and is characterized by the pruning of synapses, elaboration of dendritic arborization (Changeux & Danchin, 1976; Huttenlocher, 1990), and increased myelination (Jernigan, Trauner, Hesselink, Tallal, 1991; Pfefferbaum et al., 1994; Yakovlev & Lecours, 1967). Having provided a basic overview of typical brain development that takes place during childhood and adolescence, I will now discuss in detail the changes that occur in gray and white matter development across childhood and adolescence that characterize this refining process.

### **Gray Matter Development**

Humans are born with an over abundance of neuronal synaptic connections. After approximately the age of 2, however, synaptic pruning occurs such that synapses that are not being used are eliminated to enhance computational capacity and speed of information processing (Goldman-Rakic, 1987). A mechanism of brain plasticity called activity-dependent stabilization underlies the process of synaptic pruning by allowing the brain to mold or adapt to an individual's environment and then selectively prune unused synapses accordingly (Rauschecker & Marler, 1987). Synaptic pruning is believed to cause the decreases in synaptic density and gray matter volume reported to occur between 2 and 16 years of age (Huttenlocher, 1979; Huttenlocher & de Courten, 1987; Sowell & Jernigan, 1998).

The human brain develops in a hierarchical fashion with primary sensory and motor areas developing before association cortices that mediate higher order functions (Brody, Kinney, Kloman, & Gilles, 1987; Gogtay et al., 2004; Sowell et al., 2003,

Yakovlev & Lecours, 1967). One study that captured this orderly process of cortical development was done by Gogtay et al. (2004), who conducted a longitudinal study assessing changes in gray matter density in healthy children between the ages of 4-21 years of age. The analysis showed that cortical thickness (gray matter density) generally decreases with age in a “back to front” progression. Thinning of gray matter (thought to reflect synaptic pruning) began in the sensorimotor areas and subsequently progressed into dorsal and parietal, superior temporal, and dorsolateral prefrontal cortices throughout late childhood and adolescence. Using a fine-grade method of morphologic analysis, the investigators were able to detect steady decreases in cortical density across adolescence, as well as capture the protracted development of the prefrontal and superior parietal cortices found to mature in adolescence.

These results were consistent with an earlier study conducted by Giedd et al. (1999), who investigated specific developmental trajectories of gray matter maturation in various regions in the brain. This group conducted one of the largest studies of childhood and adolescent brain development, combining cross-sectional ( $n = 161$ ) and longitudinal ( $n = 145$ ; 329 scans) anatomical MRI data of healthy subjects between the ages of 4 to 21 years. The investigators found that gray matter volume in the frontal, parietal, and temporal lobes followed an inverted “U” shape developmental curve, reflecting an increase in gray matter volume before adolescence, a peak at approximately 12 years of age in the frontal and parietal cortices and at 16 in the temporal lobe, followed by a decline thereafter. Sowell, et al. (2001), found similar age-related changes in the frontal and parietal lobes; specifically, that gray matter density decreased over the dorsal frontal



and parietal lobes between childhood (7-11 years) and adolescence (12-16 years), with continued decline in the frontal cortex between adolescence and adulthood (23-30 years).

Additional imaging studies (Sowell & Jernigan, 1998; Thompson et al., 2000) as well as early pathological studies (Huttenlocher, 1990; Huttenlocher & Dabholkar, 1997; Rakic, Bourgeois, & Goldman-Rakic, 1994), demonstrated similar decreases in gray matter volume in frontal and parietal regions throughout childhood and adolescence as well. Although this decrease in gray matter density is thought to be mostly due to synaptic pruning (Sowell & Jernigan, 1998; Thompson et al., 2000), the literature suggests that additional processes including neuronal loss and an increase in myelination may be contributory as well (Steen, Ogg, Reddick, & Kingsley, 1997; Sowell et al., 1999). Although significant maturational changes occur in the cerebral cortex during adolescence, this is particularly evident in the prefrontal cortex, which has been identified as the last area of the brain to reach full maturation (Giedd et al., 1999; Gogtay et al., 2004; Mukherjee et al., 2002; Paus et al., 2001; Sowell et al., 2001).

### **White Matter Development**

Although most myelination in brain white matter is complete by the age of 5 (Nakagawa et al., 1998), white matter maturation continues into at least the third decade of life (Pfefferbaum, Mathalon, Sullivan, Rawles, Zipursky, & Lim, 1994; Huttenlocher & Dabholkar, 1997). This white matter maturation is essential for increasing neuronal transduction and speed of information processing that subserves the development of cognitive, behavioral, emotional, and motor functions into adulthood (Schmithorst et al., 2005).

Different methodologies have been used to study white matter development. Previous postmortem histological studies have shown that axonal diameter and the myelin sheath demonstrate marked growth from birth to 2 years of age (Brody, Kinney, Kloman, & Gilles, 1987). Postmortem literature also suggests that there is a continued increase in white matter myelination throughout childhood and adolescence (Benes, Turtle, Khan, & Farol, 1994; Yakovlev & Lecours, 1967). However, these studies are limited by small sample sizes.

MRI analyses of brain development *in vivo* have consistently reported increases in white matter volume and density from childhood to adolescence (Reiss et al., 1996; Giedd et al., 1999; Paus et al., 1999; Pfefferbaum et al., 1994). These changes are thought to mostly reflect continued myelination (Giedd et al., 1999; Sowell, et al., 2004; Yakovlev & Lecours, 1967) and increases in axonal diameter (Paus et al., 1999; Reiss et al., 1996; Steen, Ogg, Reddick, & Kingsley, 1997). The process of myelination is very orderly, and proceeds from posterior to anterior, as well as from dorsal to ventral regions in the brain (Yakovlev & Lecours, 1967). Sensory regions are myelinated before motor regions, and central regions before peripheral (Bird et al., 1989; Brody, Kinney, Kloman, & Gilles, 1987; Cristophe et al., 1990; Dekaban, 1978). The prefrontal cortex is the last region of the brain to myelinate, particularly the dorsolateral regions, as this area continues to myelinate into the third decade of life (Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus,, 1999; Yakovlev & Lecours, 1967).

Diffusion tensor imaging (DTI), a newer MRI technique, has been helpful in identifying and characterizing the integrity of white matter pathways that subserve functional neural networks in the brain. Based on the early work by Le Bihan and Breton

(1985), and later work by Bassar, Mattiello, and Le Bihan (1994), DTI allows us to look at the integrity of axonal fibers, the manner in which they integrate to form fiber bundles, and their ability to form efficient neural pathways. The DTI literature has consistently reported age-related changes in maturation of white matter microstructure, which include increased myelination, axonal diameter, number of axons per cross-sectional area, and the organization/ coherence of these fibers (Barnea-Goraly et al., 2005; Mukherjee et al., 2002; Mukherjee et al., 2001; Nagy, Westerberg, & Klingberg, 2004; Schmithorst et al., 2002). Specifically, a strong positive correlation between white matter microstructural integrity in major white matter tracts and age has been found throughout childhood and adolescence (Mukherjee et al., 2001; Schmithorst et al., 2002; Snook, Paulson, Roy, Phillips, & Beaulieu, 2005; Zhang et al., 2005). This ongoing development of white matter microstructure in the brain increases conduction speed and overall efficiency of communication between different cortical areas (Changeux & Danchin, 1976; Huttenlocher, 1979; Yakovlev & Lecours, 1967) and is thought to underlie the advancements in cognitive and executive functioning seen during this developmental period (Braver & Barch, 2002; Bunge et al., 2002; Demetriou et al., 2002; Goldman-Rakic & Leung, 2002; Huttenlocher, 1990; Levin et al., 1991; Luciana et al., 2005; Luna et al., 2004; Marsh et al., 2006; for reviews, see Blakemore & Chowdry, 2006; Krawczyk, 2002).

### **Sex-based Differences in Brain Development**

Despite similar developmental patterns, important sex-based differences exist in neural development during adolescence. Regional sex-based differences in cortical and subcortical brain maturation are partly attributable to significant differences in sex steroid

development and puberty between boys and girls (Filipek, Richelme, Kennedy, & Caviness, 1994; Giedd, Castellanos, Rajapakse, Vaituzis, & Rapoport, 1997; Goldstein et al., 2001, Sowell et al., 2002; Wilke, Krageloh-Mann, & Holland, 2007). Before discussing these differences, a brief overview of the hormonal changes that occur during puberty will be discussed. Specifically, there are three main endocrine events that take place during this time, and which exert profound effects on brain maturation and behavior: (Cahill, 2006; Sisk & Foster, 2004); these are adrenarche, gonadarche, and activation of the growth axis (Cahill, 2006; Dorn, 2006; Sisk & Foster, 2004; Spear, 2000).

Typically, activation of the hypothalamic-pituitary-adrenal axis occurs between the ages of 6 and 9 years in females, and 7 and 10 years in males (Dorn, 2006; Grumbach & Styne, 1998). This process is called adrenarche, and is characterized by the rise of adrenal androgens, which contribute to the development of secondary sexual characteristics (Dorn, 2006). Adrenarche usually peaks at approximately 20 years of age (Worthman & Stallings, 1997).

In their review, Blakemore, Burnett, and Dahl (2010), describe gonadarche as a biological process that begins with activation of the hypothalamic-pituitary-gonadal axis, and ends with the attainment of reproductive competence. This process usually occurs between the ages of 8 and 14 years in females, and 9 and 15 in males, and is characterized by the release of gonadotropin-releasing hormone (GnRH) from the hypothalamus. This in turn stimulates pituitary production of luteinizing hormone (LH) and follicle-stimulating hormone (FSH), which activate maturational changes in gonads, and subsequent secretion of gonadal steroids, estrogen and testosterone. The increase in

gonadal steroids triggers changes in reproductive organs and the appearance of secondary sexual characteristics (Susman & Rogol, 2004). Activation of the growth axis is another hormonal event, which occurs at approximately age 12 in girls, and 14 in boys, and results in a linear growth spurt and changes to body size and composition (Marshall & Tanner, 1969, 1970). Gonadal steroid hormones not only influence appearance of the body, but activate neural circuits during puberty for adult social and reproductive behaviors (Sisk & Foster, 2004). It has been suggested that the hormonal events of puberty trigger a period of structural reorganization and plasticity in the brain, which is thought to contribute to the sexual dimorphism seen in neural brain development (Sisk & Foster, 2004).

Much of the literature on adolescent brain development suggests that neurodevelopmental trajectories are significantly different between boys and girls (De Bellis et al., 2001; Lenroot et al., 2007). For example, adolescent males (and males in general) have 9-12% larger brain volumes than females, even after accounting for sex differences in height and weight (De Bellis et al., 2001; Giedd et al., 1997; Reiss et al., 1996). In addition, total cerebral volume has been shown to peak earlier for adolescent females, at 10.5 years, compared to adolescent males, at 14.5 years old (Lenroot et al., 2001). Regional gray matter volume tends to peak approximately 2 years earlier in females compared with males (8.5 for females and 10.5 for males), and similarly, subcortical gray matter tends to peak earlier in females as well (Perrin et al., 2008). The age at which gray matter volume peaks has been associated with the sexually dimorphic ages of gonadarche onset, suggesting a possible interaction between puberty hormones and gray matter development (Neufang et al., 2009; Peper et al., 2009).

White matter volume in males, on the other hand, tends to grow more rapidly than in females during adolescence (Lenroot et al., 2007). A study by Perrin et al. (2008), investigated the relationship between expression levels of a gene encoding the androgen (testosterone) receptor and white matter development in males. They found that the variance in trajectory of white matter development was related to gene expression levels suggesting a major contribution of testosterone to the sexually dimorphic relationship between age and white matter development.

Although many of the regional volumetric differences can be attributable to varying brain size, adolescent males have been shown to have more white matter volume in the frontal lobes, while females have been shown to have more gray matter in the frontal lobes, even after controlling for total brain size (Lenroot et al., 2007; Schmithorst, Holland, & Dardzinski, 2008). Interestingly, gray matter is comprised of somatodendritic tissue, which is thought to be associated with more computational processing; whereas white matter is myelinated connective tissue needed for information transfer across distant regions of the brain (Gur et al., 1982). Thus, a higher percentage of gray matter in women is thought to increase the proportion of tissue available for computational processes (Gur et al., 1982).

In summary, adolescence is marked by an important neurorefining process with documented non-linear decreases in gray matter volume, and increases in white matter. Although this refining process is similar for both boys and girls, there are significant differences in neurodevelopmental trajectories between the sexes, which have been associated with puberty and sex-specific hormonal development. Not only do these underlying processes affect neurodevelopment, but they are likely related to the

cognitive, emotional, and behavioral differences seen throughout this developmental period. In particular, this continued refining process is thought to subserve the protracted development of many executive functions.

### **Executive Functions**

Executive functioning is an umbrella term used to represent higher order abilities involved in goal-oriented behavior (Lezak, 1995; Luria, 1966; Shallice, 1982). Executive functions encompass the highest level of human functioning including intellect, thought, self-control, and social interaction (David, 1992), and are responsible for the synthesis of external stimuli, preparation for action, and the appropriate execution of action (Luria, 1973). According to Lezak (1982), executive processes are integral in formulating goals, planning how to achieve them, and carrying out these plans effectively, and are “the heart of all socially useful, personally enhancing, constructive and creative activities” (p. 281). Executive functioning is a collection of inter-related mental processes responsible for goal-directed, future-oriented behavior, and has been referred to as a conductor that controls, organizes and directs cognitive activity, emotional responses, and behavior (Gioia, Isquith, & Guy, 2001).

The mental processes comprising executive function can be dichotomized into cognitive and emotional capacities (Anderson, 2008; Gioia, Isquith, Guy & Kenworthy, 2000; Zelazo, Qu, & Muller, 2004). The cognitive capacities are referred to as “cool” executive functions and include anticipation and deployment of attention, impulse control, behavioral control and self regulation, working memory, mental flexibility and utilization of feedback, goal setting, strategic planning ability and organization, initiation of activity and selection of efficient problem solving strategies (Anderson, 2008; Fuster,

2002; Hughes, 1998; Weyandt & Willis, 1994). The emotional capacities are referred to as “hot” executive functions and consist of empathy, theory of mind, emotional regulation, and affective decision-making (Happaney, Zelazo, & Stuss, 2004; Kerr & Zelazo, 2004). These are required when a situation is emotionally meaningful and involves regulation of affect and motivation, and thus, these functions are essential to our organization and execution of purposeful behavior (Anderson, 2008; De Luca, & Leventer, 2008; Happaney et al., 2004; Kerr & Zelazo, 2004). Despite having a theoretical distinction, cool and hot executive functions are considered intimately connected and are consistently utilized in combination for daily functions.

In combination, these hot and cold executive functions are thought to provide humans with the unique capacity for experiencing guilt and self-reflection, as well as purposefully mediating one’s ability to interact with his/her surroundings in a meaningful, constructive, and autonomous manner (De Luca, & Leventer, 2008). Shallice (1988) described executive function as a “supervisory attentional system” that assists in inhibiting and overriding reflexive behaviors in order to produce more controlled, situationally appropriate, and adaptive responses. These processes allow us to attend to relevant information while simultaneously inhibiting irrelevant information, all of which are very important in cognitive and behavioral regulation, planning and decision-making (Casey, Durston, & Fossella, 2001).

### **Cognitive and Executive Functions Develop Across Adolescence**

Executive functions are thought to develop across the lifespan, from infancy to adulthood. Each executive function has a unique developmental trajectory characterized by specific cognitive, behavioral and structural milestones (De Luca, & Leventer, 2008).



Although it is unclear whether executive functions develop in a stage-like or linear manner, the literature consistently supports the idea that maturation of executive functions is highly correlated with brain development. Specifically, the protracted development of many executive functions has been associated with the delayed maturation of the prefrontal cortex (Anderson, 2002; Casey et al., 2000; Espy, 2004; Luciana et al., 2005; Luciana & Nelson, 1998).

One way that executive functions are measured is through neuropsychological assessment. The literature indicates that many prefrontally-mediated executive functions are present in their most basic and fundamental forms early in development (Bell & Fox, 1992; Diamond & Goldman-Rakic, 1989). However, with age comes the development of more complex, multifactorial skills as well as a refinement of pre-existing basic functions (Davies & Rose, 1999; Levin, Culhane, Hartmann, Evankovich, & Mattson, 1991). The evidence of developmental spurts in executive functioning skills at various ages, characterized by the development of new awareness or strategy that was not previously available to the child, is thought to reflect maturational events in the frontal areas of the brain (Anderson, Anderson, Northam, Jacobs & Catroppa, 2001; Bell & Fox, 1992; Casey et al., 2000; Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004).

Although information about the cognitive advances that occur during infancy and childhood have been well-documented in the literature, relatively less is known of the mechanisms that support later development during adolescence. In her review, Luna (2009) describes the developmental behavioral transition that occurs from immature mechanisms during infancy and early childhood, to more adult-like behavior during adolescence and early adulthood. Specifically, early development is characterized by

pronounced changes in behavior with the acquisition of simplistic skills, while later development involves more subtle changes as abilities become more sophisticated with maturity during adolescence. Significant landmarks of this developmental phase during adolescence include an increase in endogenously driven behavior that is controlled, voluntary, planned, and driven by internal goals. There is also an increase in cognitive flexibility and control, abstract thought and rule-guided behavior (Asato, Sweeney, & Luna, 2006; Bedard et al., 2002; Demetriou et al., 2002; Fukushima et al., 2000; Luna, et al., 2004; Ridderinkhof, Band, & Logan, 1999; Wise, Sutton, & Gibbons, 1975).

As stated above, the protracted development of many executive functions is thought to be the underlying mechanism accounting for the increase in controlled and voluntary behavior present during adolescence. Specific executive functions that demonstrate this protracted behavioral maturation, which do not reach adult levels of performance until late adolescence, include working memory (Demetriou et al., 2002; Luna et al., 2004), selective attention and response inhibition (for reviews see, Diamond 2002; Welsh 2002), and response planning and preparation (Anderson et al., 2001). These functions are thought to improve with age, practice, and vary with motivation and intelligence (Damon & Lerner, 2008). Although not considered an executive function, processing speed, which is required for many higher order cognitive skills and executive functioning abilities, has also been shown to improve from early childhood to mid-adolescence (Demetriou et al., 2002; Kail, 1991, 1993; Luna et al., 2004).

As stated above, this study has a primary emphasis on looking at the PASAT as a measure of executive functioning. However, the PASAT has been shown to require the integration of various complex cognitive processes (Audoin et al., 2003; Christodoulou et

al., 2001; Chronicle & MacGregor, 1998; Cicerone, 1997; Cicerone & Azulay, 2002; Di Stefano & Radanov, 1995; Dyche & Johnson, 1991; Gronwall, 1986; Litvan, Grafman, Vendrell, & Martinez, 1988; Radanov, Hirlinger, Di Stefano, & Valach, 1992; Snyder & Cappelleri, 2001; Spreen & Strauss, 1998; Webbe & Ochs, 2003). Therefore, each of these skills will be reviewed in depth below. Specifically, the developmental changes in attention, working memory, response inhibition, and processing speed are addressed, as these cognitive skills are necessary for performance on the PASAT.

### **Attention**

Attention is often described as the cognitive process of selectively concentrating on, and allocating processing resources to certain information, while filtering or ignoring extraneous information (Anderson, 2004). There are many different types of attention. However, to review each of these in depth extends beyond the scope of this paper. In this section, attention, as a broad term, and as a contributing factor to executive functioning, will be discussed. In addition, the construct and development of sustained attention will be reviewed, as this skill is particularly important in performance on the PASAT (Dyche & Johnson, 1991; Gronwall, 1986; Spreen & Strauss, 1998).

Attentional processes are a fundamental importance to human behavior, for it is attention that determines the source of information that will be considered (Anderson, 2004). Attention is involuntarily captured by changes in the sensory environment and the ability to detect novel or unusual events in the environment is essential to survival.

Attentional control is considered by some researchers as essential to success on all executive tasks (Senn, Epsy, & Kaufman, 2004). This skill is, therefore, thought to come on-line earlier in life, and to contribute to the development of more specialized executive

functions, such as planning and organization, by progressively expanding the processing capacity of the brain during adolescence and early adulthood (Smidts, Jacobs, & Anderson, 2004). Strong attentional abilities allow for the filtering of distractors and sustained focus on goal-directed behavioral planning, which is key to optimally adaptive and functional behavior (Luna et al., 2004).

Attention is often measured through reaction time and/or response accuracy, as these are considered reflections of an individual's susceptibility to distraction or interference (Luna et al., 2004). Research has shown that younger children (between the ages of 8 and 10 years of age) tend to react more slowly, and make significantly more inattentive, impulsive, and distractibility errors, compared to children between the ages of 10 and 12 years (Becker et al., 1987; Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004). Attention is often affected by fatigue, stress, motivation, and habituation (Caggiano & Parasuraman, 2004; Fisk & Schneider, 1981).

Many types of attention demonstrate a non-linear developmental trajectory, changing rapidly in early childhood, and plateauing during later childhood and adolescence. However, some attentional processes, such as selective attention, or the ability to attend to relevant stimulus dimensions while ignoring irrelevant ones (Chelune & Baer, 1986; Welsh, Pennington, & Grossier, 1991), are thought to be progressively refined throughout adolescence, and continue to develop into adulthood (Brodeur, Trick, & Enns, 1997; Karatekin, 2004; Klimkeit et al., 2004; Kwon, Reiss, & Menon, 2002; Plude, Enns, & Brodeur, 1994). Because selective attention is a highly integrated component of response inhibition, it is discussed more thoroughly in a different section below.

As stated above, sustained attention is a very important cognitive skill required for the PASAT (Dyche & Johnson, 1991; Gronwall, 1986; Spreen & Strauss, 1998). Sustained attention is a term that is often used interchangeably with vigilance, and is defined as the endogenous controlled capacity to actively detect, select, and respond to relevant stimuli over prolonged periods of time (Cowan, 1995; Davies & Parasuraman, 1982). Whereas attention usually refers to a more focused activation of cerebral cortex that enhances information processing, sustained attention is the maintenance of attention-requiring performance (Mackworth, 1969).

Unlike selective attention, however, sustained attention develops early on in life, reaching adult levels by early adolescence. Greenburg and Waldman (1993) studied sustained attention using the Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) in children aged 6-16 years and found that sustained attention develops in a stepwise-fashion, changing rapidly early on, and plateauing in early adolescence. Specifically, several researchers have found that the most rapid increases in the ability to maintain sustained attention occurs between the ages of 4 to 6, and 8 to 10, with subsequent and more gradual changes between the ages of 10 and 13 (Gale & Lynn, 1972; Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004; Rebok et al., 1997).

Although sustained attention develops early on in life, reaching adult levels by early adolescence, it is an integral component of many higher order executive functions that develop later on, including working memory and response inhibition, which allow for more complex cognitive processing to occur.

### **Working Memory**

According to Baddeley (2000), working memory can be defined as a limited capacity system allowing the temporary storage and manipulation of information necessary for such complex tasks as comprehension, learning and reasoning. It is the ability to maintain and manipulate information online, and is essential for voluntary control of behavior based on internal plans (Baddeley, 1986). On tasks assessing working memory, an individual is required to hold information in their mind to be recalled later, while simultaneously performing an intervening task (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Case, Kurland & Goldberg, 1982; Hitch, Towse & Hutton, 2001). This requires the individual to keep the original information online during the delay period (which is often filled with other distracting tasks) in order to accurately guide the participant's response choice at a later time. This response accuracy (with respect to the previously presented information) is used to characterize the integrity of working memory (Hikosaka & Wurtz, 1983; Zald & Iacano, 1998).

According to Baddeley's (2000) most recent theoretical model, working memory is comprised of four components including the central executive, phonological loop, visuo-spatial sketch-pad, and the episodic buffer. Briefly, the functions of the central executive include selectively attending to pertinent information, while ignoring irrelevant information in order to facilitate multi-tasking. This is done by coordinating adequate working memory resources across various concurrent activities, switching attention, and providing a response set within a various task that requires mental flexibility and retrieval of information from long-term memory to respond to demands of the environment (Baddeley, 1996; 2002). The phonological loop temporarily maintains and manipulates speech-based information while the visuo-spatial sketch-pad holds and manipulates

visuo-spatial information. The episodic buffer is controlled by the central executive and provides a workspace for the temporary storage of information. It also integrates information from the phonological loop and visuo-spatial sketch-pad with long-term memory to create a unitary episodic event of representation (Baddeley, 2000).

Although the basic modular structure of Baddeley's working memory model is thought to be present by early childhood (4 to 6 years of age), each component of this model increases in capacity and efficiency until adolescence (Gathercole, Pickering, Ambridge, & Wearing, 2004). Early in development, verbal and visuospatial working memory is thought to be fractionated and regulated by separate, domain-specific systems. For example, verbal information is processed using the phonological loop, and non-verbal information, using the visuo-spatial sketchpad. This modality-specific working memory processing system is able to support the more basic, immature working memory functions of infancy and early childhood. However, after the age of 8, a shift occurs where the child replaces this fractionated information processing system with a phonological approach to both verbal and non-verbal stimuli (Fenner, Heathcoat, & Jerrams Smith, 2000; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hitch, Wooden, & Baker, 1989; Luciana & Nelson, 1998; Palmer, 2000). For example, Brocki and Bohlin (2004) found that performance on working memory tasks improved at 2 distinct developmental points, the first occurring around the age of 8, and the second, around the age of 12. The investigators hypothesized the first developmental spurt to be attributable to a shift in the coding style of non-verbal stimuli, from predominantly using a visual coding form, to using a phonological approach as the child learns to verbally encode information. This coding type has been shown to improve recall (Hitch et al., 1988). The

latter developmental spurt may reflect the protracted course of working memory development and the maturation of phonologic, verbal strategies to improve accuracy and rate of information processing (Brocki & Bohlin, 2004).

As stated above, working memory shows a protracted development throughout adolescence (Demetriou et al., 2002; Luciana et al., 2005; Luna et al., 2004). The literature suggests that processes supporting the maintenance of general and simplistic working memory tasks are available early in development, as children are able to use previously presented information that is stored in working memory to guide subsequent behaviors and responses (Luciana et al., 2005; Nelson, Thomas, & Haan, 2008; van Leijenhorst, Crone, & van der Molen, 2007). However, general working memory processes tend to be less accurate in childhood and are fine-tuned throughout adolescence and even into adulthood (Luna et al., 2004; Zald & Iacano, 1998). For example, the ability to direct one's actions into the future emerges in late infancy (Diamond, 1990). This is followed by an improvement in simple set shifting abilities and maintenance of multiple response dimensions during preschool and into middle childhood (Zelazo, Frye, & Rapus, 1996; Zelazo & Reznick, 1991). Executive control over information being held in memory seems to develop with increasing precision in middle childhood (Luciana & Nelson, 1998; Passler, Isaac, & Hynd, 1985; Welsh, Pennington, & Groisser, 1991). Throughout adolescence, working memory functions become more refined and sophisticated with increased encoding accuracy, response precision, and efficiency of information processing (Brocki & Bohlin, 2004; De Luca et al., 2003; Demetriou et al., 2002; Zald & Iacano, 1998). This continuous fine-tuning of working memory supports



the maintenance of more detailed active working memory representations, as well as increased accuracy and precision (for review see Luna, 2009).

One study that highlights this process was conducted by Hale, Bronik, and Fry (1997) who examined the development of both verbal and visuospatial working memory development in children and adolescence. Specifically, they compared the performance of two groups of children, ages 8 and 10, with a group of older individuals, age 19, on tasks of verbal and non-verbal working memory. The investigators found a linear relationship between age and working memory span, with the 19-year-olds performing significantly better than the 10-year-olds, who in turn performed better than the 8-year-olds.

Gathercole, Pickering, Ambridge, and Wearing (2004) assessed changes in working memory performance across age. With a sample size of over 700 participants ranging in age between 4-15 years old, they captured developmental changes in test performance on 3 tasks of verbal working memory. Specifically, each participant was administered a backward digit recall test, listening recall test, and a counting recall test, along with simple verbal and visual maintenance tasks for comparison. The authors found that performance on these working memory tasks improved significantly and linearly with age.

In an attempt to characterize spatial working memory development through adolescence, Luna et al. (2004), looked at the performance of 245 healthy participants between the ages of 8 and 30 on an oculomotor working memory task. Results indicated that at the age of 19, performance plateaued and reached full maturation for the ability to

accurately fixate remembered locations, a task which reflects spatial working memory capacity.

### **Response Inhibition**

Response inhibition is the ability to voluntarily control one's behavior by suppressing task-irrelevant responses for more task-appropriate responses (Fuster, 1989; Miller & Cohen, 2001). It is an essential skill for choosing a course of action based on a cognitive plan over alternative task-irrelevant behaviors (Bjorklund & Harnishfeger, 1995; Demster, 1992; Luna et al., 2004). Response inhibition can be broken down into two distinct types. The first is the ability to inhibit attention toward interfering stimuli. This is otherwise known as selective attention (Demetriou et al., 2002). The second is the ability to inhibit the use of a previously learned and well-established response in order to appropriately complete a task (Fuster, 1997). In this situation, one forgoes the more natural, reflexive, automatic response and instead applies a more effortful response strategy. The ability to voluntarily inhibit responses provides flexibility to choose actions and for behavior to be guided by a task goal (Fuster, 1997). It also allows for the filtering of distracters in order to focus on response planning and preparation (Bjorklund & Harnishfeger, 1995; Demster, 1992). Response inhibition has been measured with tasks that require cessation of a reflexive response or suppression of interference from established responses that are incompatible with the goal of the task (Luna et al., 2004).

Voluntary response inhibition is a cognitive skill that develops throughout childhood (Fisher, Biscaldi, & Gezeck, 1997; Levin, Culhane, Hartmann, Evankovich, & Mattson, 1991; Luciana & Nelson, 1998; Munoz, Broughton, Goldring, & Armstrong, 1998; Paus, Bebenko, & Radil, 1990) and adolescence (Luna et al., 2004; Ridderinkhoff,

Band, & Logan, 1999; Ridderinkhoff, van der Molen, Band, & Bashore, 1997). It has been reported that inhibitory control improves steadily during adolescence, and possibly beyond (Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004). Although the basic ability to inhibit a response as an isolated event is present during early infancy (Amso & Johnson, 2005; Bell & Fox, 1992; Diamond & Goldman-Rakic, 1989), the actual rate of consistently and accurately inhibiting a response is what improves over time (Bedard et al., 2002; Luna et al., 2004; Ridderinkhof et al., 1999; Van den Wildenberg & van der Molen, 2004; Williams, Ponesse, Schacher, Logan, & Tannock, 1999; Wise, Sutton & Gibbons, 1975).

Research has indicated that adolescents perform far better than children on learning tasks due to a superior ability to attend to relevant stimuli, while ignoring irrelevant and potentially interfering information (Bedard et al., 2002; Luna et al., 2004; Ridderinkhof et al., 1999; Van den Wildenberg & van der Molen, 2004; Williams et al., 1999; Wise et al., 1975). A study by Luna et al. (2004) demonstrated a dramatic improvement in performance on tasks of response inhibition with age, reaching adult levels of performance by approximately 14 years of age. Specifically, the investigators found a twofold decrease in the number of response suppression errors from childhood (ages 8–9) to adolescence (ages 16–17), which slowly continued to improve into adulthood (ages 20–25). The investigators concluded that the ability to suppress contextually inappropriate responses when inhibitory demands are low is present early on in childhood. However the ability to consistently and accurately inhibit a response, regardless of task demand, continues to improve throughout adolescence. As with working memory, this transition into mature levels of response inhibition involves

improvements in the use of a pre-existing ability, rather the acquisition of new processing capacities. These results are consistent with several other studies as well (e.g., Fukushima et al., 2000; Hagen & Hale, 1973; Klein & Foerster, 2001; Schiff & Knopf, 1985; Williams et al., 1999).

The literature suggests that with maturity comes the ability to establish a task-related state in which cognitive and sensory demands are consistently orchestrated to carry out inhibitory responses (Logan & Gordon, 2001). This task-related state supports the flexible and consistent use of the ability to inhibit responses and allows for the executive organization and control of the processes guiding cognitive events. Thus, the ability to efficiently use these inhibitory skills in a flexible and consistent fashion by effectively establishing a response state is what characterizes development throughout adolescence and adulthood.

### **Processing Speed**

Processing speed, the speed by which one is able to execute basic cognitive processes to produce a response, is often measured by reaction time. Processing speed is thought to be indicative of the integrity of the neurophysiologic processes underlying functional integration, which support cognitive development (Kail 1993). Processing speed consistently predicts performance on a variety of other cognitive tasks (Kail & Ferrer, 2007). For example, more rapid processing speed is associated with increased capacity of working memory, enhanced inductive reasoning, improved response inhibition, and greater accuracy in solving arithmetic word problems (Fry & Hale, 1996; Kail, 2007; Kail & Ferrer, 2007; Kail & Hall, 1999; Luna et al., 2004).

The developmental profile associated with processing speed indicates an exponential increase in processing speed on cognitive and reflexive tasks throughout childhood and adolescence (Hale, 1990; Kail, 1993). According to Kail (1991) there is a substantial increase in processing speed during early and middle childhood. Between late childhood and early adolescence, processing speed continues to increase, although not quite as rapidly. In mid-to-late adolescence, processing speed reaches asymptotic values and begins to level off.

A study that highlights this developmental increase in processing speed was conducted by Kail (1986) and compared performances of individuals from 12 different age groups, ranging from 8 to 15, and 18 to 21 years of age. The participants were asked to judge whether pairs of pictures were identical physically, or in name. Response times were used to estimate the time it took to retrieve object names from long-term memory. Results showed a substantial decline in retrieval time from 303 milliseconds (ms) to 147ms between the ages of 8 and 11, and a milder decline from 147 to 99ms between age 11 and 14 years of age. This study demonstrated the aforementioned substantial increase in processing speed between early and middle childhood, with a milder increase between middle childhood and adolescence.

Developmental improvements in the speed of processing have been well documented throughout the literature on a variety of tasks including simple reaction time tasks (Fischer et al., 1997; Fukushima et al., 2000), inhibitory control tasks requiring more cognitive demand (Luna et al., 2004; Munoz et al., 1998), manual reaction time tasks (Elliott, 1970), and visual matching tasks (Fry & Hale, 1996). Regardless of task

type or difficulty, the evidence suggests there is a similar developmental increase in processing speed that reaches maturity in adolescence (Hale, 1990; Kail, 1993).

### **Integration of Executive Functions**

In summary, all of the aforementioned cognitive processes outlined above are required for successful performance on the PASAT. With the exception of sustained attention, which develops earlier on in life, working memory, selective attention/response inhibition, and processing speed all demonstrate a developmental trajectory that continues across childhood and adolescence. Although each of these cognitive functions develop independently of one another, and have their own unique developmental trajectories, it is the effective integration of these functions that is essential for the execution of higher order voluntary, planned behavior. Integral steps involved in this type of behavior include the ability to actively detect and attend to relevant stimuli over prolonged periods of time (sustained attention; Cowan, 1995; Davies & Parasuraman, 1982), efficiently prioritize and process simultaneous information (selective attention; Stinson, C. 2009), manipulate information while retaining the goal of a response online (working memory), and plan and prepare a response while filtering out task irrelevant responses (response inhibition; Luna, 2009).

Thus far, I have discussed general information regarding the cognitive processes required for successful completion of the PASAT. I have reviewed their respective developmental trajectories as unique, individual processes, as well as provided information regarding the importance of their integration to support the execution of higher order, executive-reasoning skills. While a basic understanding of this general information is important for the purposes of this paper, there are also important sex-based

differences in cognitive development and functioning that are relevant, and which will be outlined in the next section below.

### **Sex Based Differences in Cognitive Functioning**

Earlier in this paper, general neurodevelopment across adolescence was reviewed, along with important sex-based differences in hormonal development and puberty, which are thought to contribute to sex-specific neurodevelopmental trajectories. This consists of differences in brain volume and distributions of white and grey matter between the sexes, which are thought to underlie important sex-based differences in cognitive abilities (for review, see Marsh et al., 2008). Although sex-based differences in cognitive abilities between adult males and females have been widely documented in the literature, these differences are more modest and less prevalent in the adolescent research literature (for review, see McCarthy & Konkle, 2005). Generally, adult males have been found to have better spatial abilities, outperforming females on tasks of mental rotation, spatial perception and rotation, and mathematical skills. Adult females, on the other hand, have been found to have better verbal skills, outperforming males on tasks of verbal fluency, manual speed, and verbal and item memory (Caplan, Crawford, Hyde, & Richardson, 1997; Collins & Kimura, 1997; Delgado & Prieto, 1996; Linn & Petersen, 1985; McGivern, Huston, Byrd, King, & Siegle, 1997).

There has been an ongoing debate in the literature regarding the existence of gender differences in math abilities and achievement (Casey, Nuttall, Pezaris, & Benbow, 1995; Gallagher & DeLisi, 1994; Halpern, 2000; Hyde et al., 1990). Some of this literature has included adolescents in addition to adult participants. While a comprehensive meta-analysis using over 100 studies to investigate gender differences in

math found little difference existed in performance on several math tasks between the two sexes (Hyde et al., 1990), other studies suggest that males outperform females in standardized tasks of mathematical achievement (Gallagher & DeLisi, 1994; Royer, Tronsky, Chan, Jackson & Marchant, 1999). These differences have also been found in select groups of high achieving and gifted children and college students (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Hyde et al., 1990). Thus, although evidence of sex-based cognitive differences has been documented for adults, findings pertaining to younger populations have been mixed. Thus, adolescents may or may not show a similar pattern given underlying brain development processes. Due to the inconsistent findings in the literature, and due to the fact that the PASAT requires the integration of multiple cognitive processes that are still developing across adolescence, a goal of this dissertation is to explore the possibility of important sex-based differences in performance on the PASAT in this adolescent population.

### **The PASAT**

In this study, I used the PASAT as a measure to more closely examine the development of executive functioning across adolescence, as well as investigate sex-based performance differences between adolescent boys and girls. The PASAT was originally developed as a research tool to investigate immediate memory and attention (Sampson, 1958; Sampson & MacNeilage, 1960). In 1974, Gronwall and Sampson used an auditory version of the PASAT in a clinical research study to assess the effects of traumatic brain injury (TBI) on *Channel Capacity*, a term borrowed from Broadbent (1958) that refers to the rate at which the nervous system transmits information, also known as processing speed. This auditory version, the PASAT-244, consisted of 244



items, divided into 4 trials presented at varying rates. Specifically, the same series of 61 pseudo-random numbers were presented 4 times, each trial at an increased rate (i.e., 2.4, 2.0, 1.6, and 1.2 seconds per digit; Gronwall & Sampson, 1974). A revised version of the PASAT, the PASAT-200, was introduced by Levin, Benton, and Grossman (1982). The PASAT-200 also consisted of four trials of increasing presentation speed. However, it was slightly shorter (50 digits per trial versus 61) and each number series was unique as an attempt to control for practice effects.

There is also a children's version of the PASAT called the CHIPASAT, which was created by Johnson, Roethig-Johnston, and Middleton (1988) to assess attention and processing speed in children and adolescents. The CHIPASAT was normed on 315 individuals (167 girls) between the ages of 8 and 14.5 years of age. This version consists of 4 trials, which are presented at a progressively faster pace than the preceding one, and which consist of 61 items each. The CHIPASAT is considered less difficult than the adult PASAT, because the complexity of the answers was restricted to a sum ranging between 2 and 10, as opposed to 2 and 18 on the adult version.

Although the PASAT has been utilized and studied in TBI research, both the full version, as well as modified versions are also extensively used in research on other medical conditions such as Multiple Sclerosis (MS; Benedict et al., 2002; Peyser, Rao, LaRocca, & Kaplan, 1990; Rudick et al., 1997), chronic fatigue syndrome, lupus, hypoglycemia, renal transplant, whiplash injury, and effects of depression on cognitive functioning (for review, see Tombaugh, 2005).

In addition to its sensitivity as a measure of processing speed (De Luca, Barbieri-Berger, & Johnson, 1994; Demaree, De Luca, Gaudino, & Diamond, 1999; Madigan, De

Luca, Diamond, Tramontano, & Averill, 2000; Ponsford & Kinsella, 1992), the PASAT has been described more recently as a multifactorial measure that requires the integration of several complex cognitive processes. These processes include sustained attention (Dyche & Johnson, 1991; Gronwall, 1986; Spreen & Strauss, 1998), auditory verbal working memory (Audoin et al., 2003; Christodoulou et al., 2001; Cicerone & Azulay, 2002; Di Stefano & Radanov, 1995; Dyche & Johnson, 1991; Litvan et al., 1988; Snyder & Cappelleri, 2001; Spreen & Strauss, 1998; Webbe & Ochs, 2003), processing ability (Cicerone, 1997), as well as inhibitory control (O'Donnell, MacGregor, Dabrowski, Oestreicher, & Romero, 1994; Spikman, Kiers, Deelman, & von Zomeren, 2001).

Many studies have demonstrated that the PASAT is a reliable and stable test, with a high degree of internal consistency ( $r = .76 - .96$ ; Crawford, Obonsawin, & Allan, 1998; MacLeod & Prior, 1996; Ponsford & Kinsella, 1992; Sherman, Strauss, & Spellacy, 1997), and strong test-retest correlations for both short- and long-term intervals ( $r = .90 - .97$ ; Dyche & Johnson, 1991; McCaffrey, Westervelt & Haase, 2001; Sjogren, Thomsen, & Olsen, 2000; Stuss, Stethem, Hugenholtz, & Richard, 1989). However, the PASAT has also been shown to be highly susceptible to practice effects, in that performance improves with repeated exposure (e.g., Beatty et al., 2003; Cohen et al., 2000; Gronwall, 1977, Gronwall & Sampson, 1974; McCaffrey et al., 2001; Stuss et al., 1989). The literature suggests that practice effects on the PASAT are likely due to the development of an effective testing strategy after the initial exposure, as well as a reduction in testing anxiety, as the novelty of the task diminishes with repeated exposure. The PASAT is frequently reported to be a very frustrating and aversive task for most participants, regardless of their cognitive status (Aupperle, Beatty, & Shelton, 2002;

Diehr et al., 2003; Holdwick & Wingenfeld, 1999; Hugenholtz, Stuss, Stethem, & Richard, 1988; Iverson, Lovell, & Smith, 2000). Regardless of cause, however, improved performance on retest raises question as to whether the initial administration adequately taps into an individual's actual ability. Since the greatest practice effects have been shown to be present on the second trial in both cognitively intact and compromised individuals, it has been suggested that scores from the second trial should be used as a baseline measure for subsequent trials.

In addition to the contributions of anxiety and practice effects with the PASAT, much of the literature on this test has focused on investigating important individual-level variables such as age, intellectual ability, education level, gender, and ethnicity on PASAT performance. Math achievement has also been considered in relation to PASAT performance. The results of these studies have been mixed (French, Ekstrom, & Price, 1963; Jastak & Wilkinson, 1974; Sherman et al., 1997).

### **PASAT and Age**

Gronwall (1977) reported that the effect of age on PASAT performance in a normative sample was minimal ( $r = -.24$ ), and that the PASAT was not suitable for children, or adults over the age of 40, as the aging process alone was sufficient to reduce scores. However, many subsequent studies have found that age is a significant predictor of PASAT performance (Brittain, LaMarche, Reeder, Roth, & Boll, 1991; Roman, Edwall, Buchanan, & Patton, 1991; Wiens, Fuller, & Crossen, 1997). Much research has found that PASAT scores decline with age in adults (Crawford et al., 1998; Diehr et al., 2003; Diehr, Heaton, Miller, & Grant, 1998; Fluck, Fernandes, & File, 2001). Additionally, Dyche and Johnson (1991), the creators of the children's version of the

PASAT (CHIPASAT), found that children under the age of 8 do poorly on the CHIPASAT. The authors attributed this to immature information processing methods and reduced mental arithmetic ability as compared to older children.

There are, however, some instances where the decline in performance with age has not held true, such that older adults have actually outperformed the young adult participants in several studies (Stuss, Stethem, & Poirier, 1987; Ward, 1997). However, the authors attributed these findings to cross-generational differences related to math ability, and familiarity with simple number bonds and addition facts rather than differences in processing speed (Egan, 1988; Roberston, Ward, Ridgeway, & Nimmo-Smith, 1996; Stuss et al., 1987; Ward 1997).

### **PASAT and Intellectual Ability**

Early research by Gronwall (1977) indicated that scores on the PASAT were not highly correlated with general intelligence ( $r = .28$ ) in a sample of military personnel. Later research confirmed this finding in a TBI population, in that PASAT performance was only minimally correlated with a measure of verbal IQ ( $r = .16$ ; Gronwall & Wrightson, 1981). Subsequent studies have suggested otherwise (e.g., Brittain et al., 1991; Egan, 1988; Roman et al., 1991; Shermann et al., 1997; Wiens et al., 1997). For example, Egan (1988) reported highly significant correlations between PASAT performance and a number of measures of intellectual functioning in a sample of healthy teenagers. An extensive study performed by Crawford et al. (1998), demonstrated a significant correlation between total PASAT scores and Full Scale IQ score (FSIQ) from the WAIS-R (Wechsler, 1981) in adults ( $r = .71$ ). More specifically, this group found that PASAT performance loaded more highly on Performance IQ ( $r = .44$ ) than Verbal IQ ( $r$

= .17), and loaded most highly on the attention index ( $r = .75$ ). In addition, multiple studies have replicated the positive relationship between the PASAT and WAIS-R FSIQ (Deary, Langan, Hepburn, & Frier, 1991; Kantar 1984; Roman et al., 1991; Sherman et al., 1997; Wiens et al., 1997), as well as with other measures of intelligence (eg. Cattell, 1973; Heim, Watts, & Simmonds, 1974; Raven, 1977; Slosson 1973; Wills & Leathem, 2004; Zachary, 1986).

### **PASAT and Education**

Findings regarding the effects of education level on PASAT performance in the literature are variable. In some cases, PASAT performance has been shown to correlate with education, in that higher education usually leads to better performance in the PASAT (Diehr et al., 1998; Stuss et al., 1987; 1989). In other cases, education was not found to be a significant, or clinically relevant predictor variable (Brittain et al., 1991; Wiens et al., 1997). However, it should be noted that in many of these studies, both IQ and education were entered into the statistical models as potential predictor variables. More often than not, IQ accounted for more variance in PASAT performance than level of education.

### **PASAT and Gender**

Many studies have found that performance on the PASAT is not affected by gender (Diehr et al., 1998; Fluck et al., 2001; Johnson et al., 1988; Macleod & Prior, 1996, Roman et al., 1991; Wingefeld, Holdwick, Davis, & Hunter, 1999). Further, researchers who have found a significant sex effect concluded that the effect size was too small to be clinically meaningful (Brittain et al., 1991; Wiens et al., 1997). For example, in one large study of 560 healthy adults, gender accounted for less than 1% of the

variance in PASAT scores (Diehr et al., 2003). Johnson et al. (1988), found no gender effect in CHIPASAT performance for 315 youth. Thus, gender does not appear to be strongly related to PASAT performance adults and children; however, no studies have looked specifically at adolescents.

### **PASAT and Ethnicity**

The effects of ethnicity on PASAT performance have not been widely studied in the literature. However, the research that has been conducted has produced mixed results. In some cases, ethnicity has been found to be a strong predictor of PASAT performance (Diehr et al., 1998, Diehr et al., 2003). In other cases, it was not found to have a significant effect (Brittain et al., 1991; Wiens et al., 1997). These researchers believed that ethnicity may not have been found to be a significant predictor in these studies because race was not equally represented throughout the different age groups in the samples, or because other demographic variables (IQ, age, education) accounted for more of the variance in PASAT performance (Brittain et al., 1991; Wiens et al., 1997).

### **PASAT and Math Performance**

Research has also indicated that PASAT performance is affected by math ability (Chronicle & MacGregor, 1998; Gronwall & Wrightson, 1981; Royan, Tombaugh, Rees, & Francis, 2004; Sherman et al., 1997; Tombaugh, Rees, Baird, & Kost, 2004). Many studies have found a moderate correlation between PASAT scores and scores on the Arithmetic subtest of the Wechsler Adult Intelligence Scale or Wechsler Intelligence Scale for Children (Crawford et al., 1998, Dyche & Johnson, 1991; Gronwall & Wrightson, 1981; Johnson et al., 1988; Sherman et al., 1997, Wills & Leathem, 2004). However, these findings are confounded by the fact that the Arithmetic subtest not only

assesses math ability, but has a strong attention component as well. Despite this overlap for the Arithmetic subtest, regression studies have found that a large portion of the variance in PASAT performance is attributable to scores on multiple math-related achievement tests that reduce the attention component (French, Ekstrom, & Price, 1963; Jastak & Wilkinson, 1974; Royan et al., 2004; Sherman et al., 1997; Tombaugh et al., 2004).

In summary, the PASAT is a well-established measure of processing speed involving attention, and other complex skills. Performance on the PASAT is clinically sensitive to brain damage from multiple disorders, and scores on the test can be influenced by both anxiety and practice effects. Further, performance on the PASAT appears to be affected by a number of individual factors including age, intellectual ability, education, ethnicity/race, and math achievement skills. There is minimal evidence to suggest that gender is significantly contributory to PASAT performance in the current literature, at least as examined in child and adult populations.

### **Study Rationale**

Although the PASAT was originally developed to assess processing speed in adults who had suffered traumatic brain injury (TBI), it has also been shown to be a sensitive measure of higher order executive functions including, selective attention, inhibition, working memory. As stated above, many of these complex cognitive processes and executive functions continue to develop into adulthood. Research indicates that the protracted development of the prefrontal cortex is the underlying mechanism that subserves the increase in controlled and voluntary behavior present during adolescence. Since much of the research has used the PASAT to assess these different cognitive and

executive functions in adult populations, its effectiveness in assessing adolescent cognitive maturation remains unclear. Broadly, the aim of the current study was to investigate the development of executive functions across adolescence in order to enhance our understanding of brain behavior relationships during this important developmental period. More specifically, I wanted to assess the relationship between age and executive functioning by examining performance on a sensitive measure of executive functioning, the PASAT, in an adolescent population. In the current study, I examined several predictor variables (Age, Sex, and IQ) of PASAT performance in a large sample of typically developing adolescents.

### **Research Questions**

Based on the preceding literature review, the following research questions were addressed in this study:

1. Is the modified adult version of the PASAT sensitive to capturing cognitive development across adolescence? In other words, is there a positive and unique relationship between PASAT performance and age in this adolescent population?
2. Is PASAT performance related to intelligence in this adolescent population? If so, what is the predictive power of IQ on PASAT performance in this adolescent population?
3. Are there significant sex-based differences in performance on the PASAT in this adolescent population that have a unique contribution relative to other variables?
4. Finally, what is the most predictive model that accounts for the greatest variance in PASAT performance in this sample?

### **Hypotheses**



Based on findings from the research literature and the subsequent research questions, the following hypotheses were tested:

- 1) Consistent with the literature, it was hypothesized that performance on the PASAT would improve with age across adolescence.
- 2) It was hypothesized that PASAT performance would be moderately correlated with intelligence (2-subscale IQ score as assessed by the Wechsler Abbreviated Scale of Intelligence) in this adolescent population.
- 3) Although research indicates that important sex-based differences in neurodevelopment exist during adolescence, most, if not all of the PASAT literature indicates that sex is not a significant predictor variable in PASAT performance. Therefore, I hypothesized that there would not be sex-based differences in PASAT performance between boys and girls in this adolescent population.

## METHOD

### Participants and Setting

Participants were 101 typically developing, right-handed adolescents between the ages of 10 and 16 years ( $M_{age} = 13.1$ ,  $SD = 1.7$ ). Right-handedness was confirmed using the Edinburgh Handedness Inventory (Oldfield, 1971). The sample was 83% Caucasian, 9% Multi-Ethnic, 4% African American, 3% Spanish, Hispanic, or Latino, and 1% Asian. Approximately 50% of the sample were boys ( $n = 51$ ). Most participants came from middle to upper class families, as measured by the Hollingshead Index of Social Position (ISP), which is based on parental occupation and years of education ( $M_{SES} = 27.32$ ,  $SD = 11.97$ ; Hollingshead, 1975). The participants were previously recruited for two larger,

ongoing grant-funded studies (Grant funding received from NIH K08 NS052147 and Dana Foundation) conducted by Bonnie Nagel, Ph.D. These larger studies were designed to investigate neural development of typical adolescents at the Developmental Brain Imaging Lab (DBI Lab) at Oregon Health & Science University (OHSU). The data used in this study were a subset of these two larger studies and were not collected for the sole purpose of conducting this study. All participants were recruited for these larger studies through flyers and word of mouth from Portland area schools and community agencies, as well as through newspaper and online advertisements.

Exclusionary criteria for participants included, the inability of a parent to provide family history information, a lifetime history of a psychiatric or substance disorder as determined by the Diagnostic and Statistical Manual of Mental Health Disorders, fourth edition (DSM-IV; American Psychiatric Association, 1994), significant substance use history (10 lifetime alcoholic drinks or 2 drinks per occasion, >5 experiences with marijuana, any other drug use, or smoking more than 4 cigarettes per day), neurological illness, significant head trauma (loss of consciousness > 2 minutes), serious medical problems, mental retardation or learning disability, current use of medications that could affect the central nervous system; significant maternal use of alcohol (4 drinks per occasion or 7 drinks per week) or other drugs during pregnancy; reported history of bipolar I or psychotic disorders in biological parents; inadequate English skills (i.e., not fluent in English); sensory problems; and left-handedness. These exclusionary criteria were implemented in an attempt to reduce abnormal neuropsychological performance, as this study is focused on typical development.

### **Materials and Procedures**

All aspects of this study were assessed and authorized by, and in accordance with OHSU's Institutional Review Board (IRB; IRB00002560). Additional authorization by Pacific University's IRB committee was obtained for this dissertation study. Prior to prescreening any potentially eligible participants, the parent/legal guardian was provided with information regarding the purpose, procedures, potential risks and benefits of the study, confidentiality was reviewed, and then a verbal consent to prescreen themselves and their child was obtained.

### **Screening**

Parent and child were prescreened separately from one another. This consisted of a short, 10-minute private telephone interview assessing basic exclusionary criteria (age, handedness, unremovable metal on or within the body, and sensory problems). After initial eligibility was determined through prescreening procedures, informed consent and assent forms were mailed to and telephone reviewed with potentially eligible families. Confidentiality was also reviewed at this time with the youth and parent by a trained DBI Lab technician. Once these assent/consent forms were signed and returned to the lab, more comprehensive telephone screens (lasting 30-45 minutes) were conducted with the youth and the parent/guardian separately, and each were compensated \$10.00 for their time. When possible, the youth and parent were interviewed by different lab assistants to facilitate open disclosure.

The youth screen consisted of the computerized NIMH Diagnostic Interview Schedule for Children Predictive Scales (DISC-PS-4.32b; Lucas et al., 2001) to assess for preexisting psychiatric disorders, the Family History Assessment Module (FHAM Rice et al., 1995) to assess for family history of substance use and other psychiatric disorders

in 1<sup>st</sup> and 2<sup>nd</sup> degree relatives, the Brief Lifetime version of the Customary Drinking and Drug use Record (Brown et al., 1998) to assess lifetime alcohol, marijuana, nicotine, and other drug use, and the Structured Clinical Interview (SCI; First, Spitzer, Gibbon, & Williams, 1997) to assess the youth's academic functioning, extracurricular activities, peer relations, family characteristics, living arrangements, health and medication history.

Similarly, the biological parent screen included the SCI (First et al., 1997), the parent version of the DISC-PS-4.32b (DISC-PS-4.32b; Lucas et al., 2001), and the FHAM (Rice et al., 1995), to corroborate and improve reliability of youth report. Additionally, the parent screen also included the Revised Socioeconomic Index of Occupational Status (Stevens & Featherman, 1981). As noted previously, the Hollingshead Index of Social Position (Hollingshead, 1975) was used to assess socioeconomic status.

### **Neuropsychological Screen**

Neuropsychological testing was completed by trained research assistants at the OHSU DBI Lab. Because this study sample was derived from participants who had previously participated in two separate, ongoing studies, the testing time and specific battery of neuropsychological tests used in each study varied. Generally speaking, however, neuropsychological testing time for these larger studies lasted approximately 1.5-3 hours, and the test batteries included a variety neuropsychological measures, personality inventories, and behavior checklists.

### **Measures**

The following measures were used for this project. Table 1 depicts the means and standard deviations for each predictor variable and two self-report symptom checklists

used in this study. There were five main variables of interest; the independent variables being age, 2-Subscale IQ, and sex, and the dependent variables being PASAT 3.0s performance, and PASAT 2.0s performance. Age was obtained from self-reports during the initial interview. Sex included 2 groups: Boys and Girls. Standard scores from the Matrix Reasoning and Vocabulary subtests from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) were used to calculate a two-scaled intelligence quotient (2-Subccale IQ). Additionally, each participant was given a modified version of the Paced Auditory Serial Addition Test (PASAT; Gronwall, 1977), which included both a three second (PASAT 3.0s) and a two second condition (PASAT 2.0s). Additionally, self-report measures were administered at the time of neuropsychological testing to screen for symptoms of psychopathology. Specifically, each participant was administered the Child Depression Inventory (CDI; Kovacs, 1992), a symptom-oriented instrument for assessing depression in children between the ages of seven and 17 years, as well as the State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), a commonly used measure that assesses trait and state anxiety.

Given the complexity of the PASAT, further information on this measure is warranted. The PASAT is comprised of two separate conditions, a three second (3.0s) and a two second (2.0s) condition. During the first condition, a single-digit number is presented at the rate of one digit every three seconds (3.0s). This is considered the easier condition of the two. During the second condition, the single digit numbers are presented at a faster rate, one every two seconds (2.0s). During both conditions, the participant listens for two consecutive numbers, calculates the sum of those two numbers in their head, and tells their answer to the administrator. They continue in this fashion, adding

each new number presented on the tape to the preceding one, for sixty trials. The participant must respond prior to the presentation of the next digit for a response to be scored as correct. Each participant is required to perform ten practice items before beginning each testing condition.

This is a very challenging task that requires the participant to simultaneously remember the last digit presented on the tape while listening for the next digit, suppression of attention to their verbal response, and performing the addition in their mind. Percent accuracy (calculated as the number of correct responses/60 trials) for each condition was used as the outcome measure of PASAT performance.

Table 1

*Descriptive Statistics of Predictor Variables for Boys, Girls, and Combined (Boys and Girls)*

Predictor Variables	Boys		Girls		Combined	
	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>	<i>n</i>	<i>M (SD)</i>
Age	51	13.16 (1.68)	51	13.08 (1.75)	102	13.12 (1.71)
WASI Abbreviated IQ	51	116.94 (10.00)	51	115.12 (11.00)	102	116.03 (10.48)
PASAT 3.0s	51	72.05 (15.94)	51	62.94 (16.96)	102	67.5 (17.00)
PASAT 2.0s	51	53.1 (13.80)	50	44.64 (15.67)	101	48.91 (15.28)
CDI	50	39.58 (4.13)	51	40.27 (5.71)		
STAI	50	38.96 (8.01)	51	39.54 (5.20)		

Note. *M (SD)* = mean (Standard Deviation); WASI = 2-scale standardized IQ score from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (3 second version; Gronwall, 1977); PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977); Child Depression Inventory (CDI; Kovacs, 1992); STAI = State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983).

## RESULTS

### **Pre-Analysis Data Screening**

Prior to conducting statistical analyses, data were carefully screened. All data were double entered into the database to reduce error in the data entry process, and all neuropsychological scores were double scored by two qualified research assistants to improve accuracy and reliability. Using the computer software program Statistical Package for the Social Sciences (SPSS; IBM, 1989, Version 19.0), I analyzed frequency distributions, checked for missing data and outliers, as well as assessed the goodness of fit between our data and the three general assumptions of normality, linearity, and homoscedasticity for each predictor variable (Age, IQ, PASAT 3.0s, and PASAT 2.0s). The entire sample was analyzed as a whole, with boys and girls combined (Combined), and then split by sex (Boy and Girl subsample groups).

Although I started with 102 participants and an equal number of boys and girls ( $n = 51$ ), PASAT 2.0s data was missing for one female participant. Thus, her data was removed from our sample, leaving a total of 50 girls and 51 boys. I found that after removing this participant, there were no more missing data points and no outliers existed that were more than three standard deviations above and below the mean for each variable. Univariate normality of each predictor variable (Age, IQ, PASAT 3.0s, and PASAT 2.0s) was assessed for all three groups (Combined boys and girls, Boy Group, and Girl Group), using the Kolmogorov-Smirnov (K-S) statistic test, with Lilliefors Significance Correction. In each case, the K-S test for each predictor variable was not statistically significant ( $p < .05$ ), indicating that each predictor variable was normally distributed. Multivariate linearity and normality was further assessed via careful review of bivariate scatterplots depicting all possible combinations of predictor variables.

Because the interpretation of these scatterplots can be quite subjective, I created



scatterplots comparing standardized residuals to the predicted values of the dependent variables (PASAT 3.0s and PASAT 2.0s percent accuracy), which suggested that the data met the assumptions of normality, linearity, and homoscedasticity. In addition, Levene's Test was used to assess homogeneity of variance in PASAT performance between boys and girls. The Levene's statistic was not significant for PASAT 3.0s ( $F = .01, p = .92$ ), and PASAT 2.0s ( $F = .06, p = .80$ ) indicating that the variability in PASAT scores between boys and girls was not significantly different.

The literature suggests that there are distinct sex-based differences in the emergence of psychopathology during adolescence (Angold, Costello, & Worthman, 1998; Castellanos et al., 1996; Castle, Sham, & Murray, 1998; Drevets, 2000). To ensure that there were no significant sex-based differences in depressive or anxious symptoms at the time of testing that could potentially impact our results, two separate independent-samples  $t$  test analyses were conducted; the first, to determine whether boys and girls significantly differed in self-report depressive symptomatology (CDI - Total  $t$  score), and the second, to determine whether boys and girls significantly differed in reported levels of anxiety (STAI - Total  $t$  score). In both cases, the  $t$  tests were not significant, indicating that reported levels of psychiatric symptomatology were not significantly different between boys and girls (CDI:  $t[99] = .70, p = .49$ ; STAI:  $t[83.80] = .43, p = .67$ ). Please refer back to Table 1 for the means and standard deviations for both of these variables.

### **Multiple Regression Analyses**

To address my first hypothesis, and determine if the independent variables of participant age, IQ, and/or sex predicted accuracy in performance on a modified version of the PASAT (Gronwall, 1977) in this adolescent sample, independent stepwise multiple regression analyses

were conducted. A stepwise multiple regression analysis was chosen because there was some uncertainty regarding the predictive nature of two out of the three independent variables used in this study (IQ and sex). Although much of the literature has shown that age is significantly related to PASAT performance, both IQ and sex were somewhat questionable. Thus, because my a-priori hypotheses were not definitive, I chose the stepwise method as it is exploratory in nature, and facilitated in building my overall regression models. The literature suggests that stepwise methods are indicated for studies that have a small number of predictor variables, which we had in this case (Mertler & Vannatta, 2005). True to its name, and inherent to the stepwise process, the stepwise linear regression analysis evaluates the order of importance of variables at each step, and based on this, selects useful subsets of variables to comprise the final regression model (Huberty, 1989; Thompson, 1995). With each variable entered into the equation, this method tests the variable's unique contribution to the model, or its redundancy. If it is considered redundant, the variable is then removed from the model (Thompson, 1989). One of the biggest weaknesses to using a stepwise method is that it uses incorrect degrees of freedom, which results in inflated statistical significance levels (Thompson, 1995; Wilkinson, 1979). Specifically, stepwise regression applies an F test to the sum of squares at each stage of the procedure. Therefore, by performing multiple statistical significance tests on the same data set, as if no previous tests had been carried out, it significantly increases the chance of committing a Type I error (Thompson, 1995; Wilkinson, 1979).

In this study, to correct for multiple comparisons and control for Type I error, the Bonferroni method was used to determine a more stringent significance level. In this study, each regression was tested at the .001 level (.05/5 predictor variables [age, sex, IQ, age-X-sex, IQ-X-sex]). Regression results indicated that the linear combination of age, IQ, and sex significantly

predicted performance on the PASAT 3.0s ( $R^2=.34$ ,  $F(3,97)=16.38$ ,  $p<.001$ ) and the PASAT 2.0s ( $R^2=.34$ ,  $F(3,97)=16.73$ ,  $p<.001$ ). For both conditions (PASAT 3.0s and PASAT 2.0s), the linear models accounted for 34% of variance in PASAT performance. Summaries of the overall regression models for PASAT 3.0s and PASAT 2.0s performance are presented in Tables 2 and 3, respectively.

Table 2  
*Regression Model Summary for PASAT 3.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
Age	.44	.19	.18	.19	23.37	<.001	1	99
IQ	.54	.29	.27	.10	13.06	<.001	1	98
Sex	.58	.34	.32	.05	7.32	.008	1	97

Note. IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (3 second version; Gronwall, 1977).

Table 3  
*Regression Model Summary for PASAT 2.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
Age	.40	.16	.15	.16	19.23	<.001	1	99
IQ	.53	.28	.27	.117	15.97	<.001	1	98
Sex	.58	.34	.32	.061	8.98	.003	1	97

Note. IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

A closer look at these regression results were used to address my next hypotheses, which were to determine how well the individual predictor variables, age, IQ, and sex, predicted performance on PASAT 3.0s and PASAT 2.0s in this adolescent population. A summary of the regression coefficients is presented in Table 4. Results indicated that age was the strongest predictor of PASAT 3.0s performance ( $\beta = .48$ ,  $p <.001$ ) and 2.0s performance ( $\beta = .45$ ,  $p <.001$ ), with an increase in performance seen across adolescence (Figure 1). Figure 1 depicts the

significant positive relationship between age and PASAT performance for the Combined (boys and girls) group (black line), as well as for the Boys group (blue line) and Girls group (red line), separately. The next strongest, significant predictor of PASAT performance was IQ, as results showed a significant positive relationship between IQ and both PASAT 3.0s performance ( $\beta = .29, p = .001$ ), and PASAT 2.0s performance ( $\beta = .33, p < .001$ ; Figure 2). Figure 2 depicts the significant positive relationship between IQ and PASAT performance for the Combined (boys and girls) group (black line), as well as for the Boys group (blue line) and Girls group (red line), separately.

Additionally, sex was also found to be a significant predictor of both PASAT 3.0s performance ( $\beta = .23, p = .008$ ), and PASAT 2.0s performance ( $\beta = .25, p = .003$ ). Follow up independent samples t-tests showed that boys performed significantly better than girls on PASAT 3.0s ( $t[99] = -2.60, p = .01, d = 0.52$ ), and PASAT 2.0s ( $t[99] = -2.90, p = .005, d = 0.57$ ), and that the effect size (Cohen's  $d$ ) of the difference in mean scores between boys and girls is of moderate practical significance (Cohen, 1988). See Table 5 for the mean percent accuracy scores, and mean and standard deviation scores for boys and girls on both conditions.

Table 4  
*Significant Predictor Variables of PASAT Performance*

Predictor Variables	PASAT 3.0s				PASAT 2.0s			
	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient
Age	.48	5.71*	.44	.50	.45	5.38*	.40	.48
IQ	.29	3.49*	.24	.33	.33	3.90*	.28	.37
SEX	.23	2.71**	.25	.27	.25	2.99**	.28	.29

Note. IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999). PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (3 second version; Gronwall, 1977). PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

\*  $p \leq .001$ , \*\*  $p \leq .008$

Figure 1. Age Significantly Predicts Performance on the PASAT

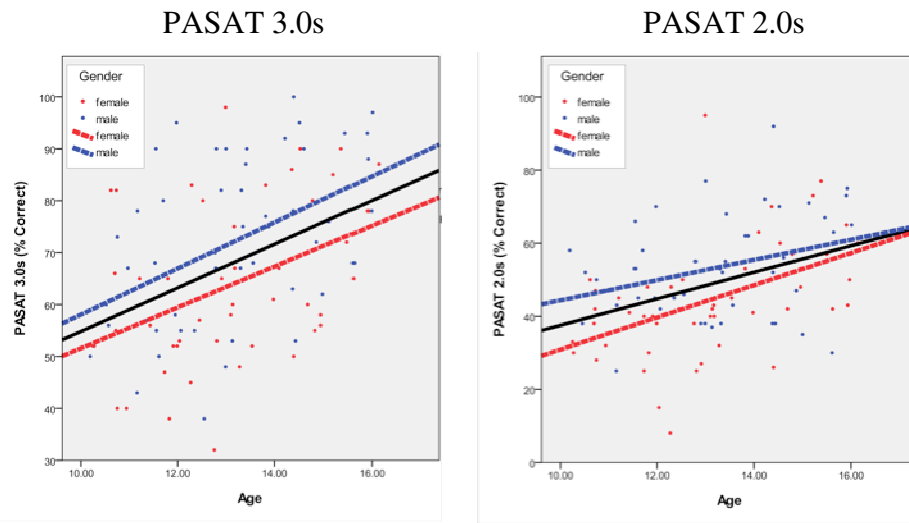


Figure 1. Age is the strongest significant predictor of PASAT 3.0s and PASAT 2.0s performance, with an increase in performance (percent accuracy) seen across adolescence. The black solid line represents the Combined (Boys and Girls) group, while the colored dotted lines represent each sex separately. While the independent variable Sex was also found to significantly predict PASAT performance, follow up independent samples t-test showed that Boys performed significantly better than Girls on both conditions of the modified version of the PASAT (Gronwall, 1977).

Figure 2. IQ Significantly Predicts Performance on the PASAT

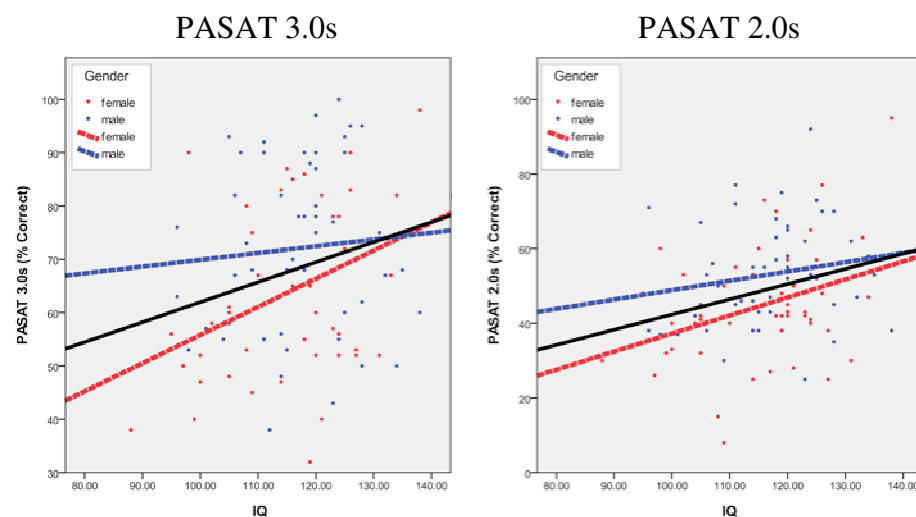


Figure 2. IQ is the second strongest predictor of PASAT 3.0s and PASAT 2.0s performance, as a significant positive relationship was found between IQ and performance (percent accuracy) in our adolescent sample. The black solid line represents the Combined (Boys and Girls) group, and the colored dotted lines represent each sex separately. While the independent variable Sex was also found to significantly predict PASAT performance, follow up independent samples t-tests showed that Boys performed significantly better than Girls on both conditions of the modified version of the PASAT (Gronwall, 1977).

Table 5

*Boys Significantly Outperform Girls*

PASAT 3.0s (% Correct)		PASAT 2.0s (% Correct)	
Boys	Girls	Boys	Girls
72 (15.94)	64 (15.80)	53 (13.80)	45 (15.67)

Note. Mean (SD)

**Follow up analyses.** Because all three independent variables, age, IQ, and sex, significantly predicted performance on the modified version of the PASAT, I wanted to ensure that the interaction effects of these variables were not better predictors of PASAT performance, above and beyond the individual variables of age, IQ, and sex alone.

***Interaction Effect for Age.*** Because the independent variable IQ in our study is based on the 2-Scale standardized IQ score from the WASI, which already accounts for, and is normed based on age, it was not necessary to include an age-by-IQ interaction variable in our follow up analyses.

To ensure that age was truly the best predictor of PASAT performance, and to rule out the chance of an age-by-sex interaction affect, follow-up stepwise multiple regression analyses with age, sex, and their interaction (age x sex) were conducted. The regression model showed that the linear combination of age and age-by-sex Interaction effects significantly predicted performance on PASAT 3.0s ( $R^2=.25$ ,  $F(2,98)=16.62$ ,  $p<.001$ ), and accounted for 25% of the variance in PASAT 3.0s performance. The independent variable, sex, was excluded from this resulting model summary. Please see Table 6 for overall regression results for PASAT 3.0s.

For PASAT 2.0s, the linear combination of age and sex were significant predictors of PASAT performance ( $R^2=.24$ ,  $F(2,98)=15.30$ ,  $p<.001$ ), but the interaction effect (age x sex) was not significant, and thus, was excluded from the model summary. In this case, the independent variables, age and sex together accounted for 24% of the variance. Please see Tables 7 for overall regression results for PASAT 2.0s.



Table 6

*Regression Model Summary: Age and Age-by-Sex for PASAT 3.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
Age	.44	.19	.18	.19	23.37	<.001	1	99
Age-x-Sex	.50	.25	.24	.06	8.17	.005	1	98

Note. Independent variable Sex was excluded from overall model; PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

Table 7

*Regression Model Summary: Age and Age-by-Sex for PASAT 2.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
Age	.40	.16	.15	.16	19.23	<.001	1	99
Sex	.49	.24	.22	.08	9.67	.002	1	98

Note. Interaction variable Age-by-Sex was excluded from overall model; PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

A closer look at the regression coefficients indicated that age alone was still the strongest predictor of PASAT 3.0s performance ( $\beta=.40$ ,  $p<.001$ ), above and beyond the age-by-sex interaction, and PASAT 2.0s performance ( $\beta=.40$ ,  $p<.001$ ), above and beyond sex alone. Please see Table 8 for a summary of regression coefficients.

Table 8  
*Age, Sex, and Their Interaction Effect as Significant Predictor Variables of PASAT Performance*

Predictor Variables	PASAT 3.0s				PASAT 2.0s			
	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient
Age	.40	4.58*	.44	.42	.40	4.54*	.40	.42
Sex	--	--	--	--	.27	3.11**	.28	.30
Age x Sex	.25	2.86**	.31	.28	--	--	--	--

Note. PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (3 second version; Gronwall, 1977). PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

\*  $p \leq .001$ , \*\*  $p \leq .005$

***Interaction Effect for IQ.*** As mentioned in the previous section, the independent variable IQ already accounted for the effect of age on PASAT performance. Therefore, an age-by-IQ interaction variable was not included in our follow up analyses. However, to ensure that the independent variables of IQ and sex, alone, were better predictors of PASAT performance, over their interaction effect, follow-up stepwise multiple regression analyses with IQ, sex, and their interaction (IQ x sex) were conducted.

The regression model showed that the linear combination of IQ and the IQ-by-sex interaction significantly predicted performance on PASAT 3.0s ( $R^2=.11$ ,  $F(2,98)=5.89$ ,  $p=.004$ ), and accounted for 11% of the variance in PASAT 3.0s performance. The independent variable, sex, was excluded from this resulting model summary, as it was not a significant predictor. Please see Table 9 for this overall regression summary for PASAT 3.0s.

For PASAT 2.0s, the linear combination of IQ and the IQ-by-sex interaction significantly predicted performance on PASAT 2.0s ( $R^2=.14$ ,  $F(2,98)=7.98$ ,  $p=.001$ ), and accounted for 14% of the variance of PASAT performance. Again, the independent variable, sex, was excluded from this resulting model summary due to nonsignificance. Please see Table 10 for this overall regression summary for PASAT 2.0s. A closer look at the regression coefficients showed that, above IQ and sex alone, the IQ-by-sex interaction was the best predictor of PASAT 3.0s ( $\beta=.23$ ,  $p=.02$ ), and PASAT 2.0s ( $\beta=.25$ ,  $p=.009$ ). Please see Table 11 for a summary of regression coefficients.

Table 9

*Regression Model Summary: IQ and IQ-by-Sex for PASAT 3.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
IQ x Sex	.26	.07	.06	.07	7.02	.009	1	99
IQ	.33	.11	.09	.04	4.52	.036	1	98

Note. Independent variable Sex was excluded from overall model; IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

Table 10

*Regression Model Summary: IQ and IQ-by-Sex for PASAT 2.0s*

Step	R	$R^2$	$R^2_{adj}$	$\Delta R^2$	$F_{chg}$	$p$	$df_1$	$df_2$
IQ x Sex	.29	.08	.08	.08	9.08	.003	1	99
IQ	.37	.14	.12	.06	6.39	.013	1	98

Note. Independent variable Sex was excluded from overall model; IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

Table 11  
*IQ, Sex, and Their Interaction Effect as Significant Predictor Variables of PASAT Performance*

Predictor Variables	PASAT 3.0s				PASAT 2.0s			
	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient	$\beta$	t-statistic	Bivariate $r$	Partial Coefficient
IQ x Sex	.23	2.32**	.26	.23	.25	2.65*	.29	.25
IQ	.21	2.13**	.24	.21	.24	2.53*	.28	.24
Sex	--	--	--	--	--	--	--	--

Note. Independent variable Sex was excluded from overall model; IQ = 2-scale intelligent quotient from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); PASAT 3.0s = Modified version of the Paced Auditory Serial Addition Test (3 second version; Gronwall, 1977). PASAT 2.0s = Modified version of the Paced Auditory Serial Addition Test (2 second version; Gronwall, 1977).

\*  $p \leq .01$ , \*\*  $p \leq .04$

## DISCUSSION

### Overview of Findings and Potential Implications

Adolescence is considered a critical period for maturation of neurobiological processes that underlie higher cognitive functions and social and emotional behavior (Coleman & Hendry, 1999; Feldman & Elliott, 1990). Neuroimaging studies have captured a subtle, yet important, refining process that takes place in the brain during adolescence, which is characterized by decreases in cortical gray matter, increases in white matter, and a protracted development of the prefrontal cortex (e.g., Barnea-Goraly et al., 2005; Giedd, 1999; Pfefferbaum et al., 1994; Reiss et al., 1996; Schmithorst et al., 2002). These important maturational processes are paralleled by the increased functional and cognitive capacities seen during adolescence. Specifically, they are thought to underlie the improvements in affective recognition, modulation, and regulation (Happaney, Zalazo, & Stuss, 2004; Kerr & Zelazo, 2004), increased speed of information processing (Elliott, 1970; Fischer et al., 1997; Fry & Hale, 1996; Fukushima et al., 2000; Hale, 1990; Kail, 1986; 1991; 1993; Munoz et al., 1998), and most notably, the development of many executive functions including attentional shifting, response inhibition, working memory, organization, abstract reasoning, decision making and planning, and goal-directed behavior seen in this age group (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Braver & Barch, 2002; Demetriou, Christou, Spanoudis, & Platsidou, 2002; Goldman-Rakic & Leung, 2002; Huttenlocher, 1990; Levin, Culhane, Hartmann, Evankovich, & Mattson, 1991; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Marsh et al., 2006).

Although the PASAT was originally developed to assess processing speed in adults who had suffered traumatic brain injury (TBI; Gronwall, 1977), it has been shown to be a sensitive measure of many cognitive, and higher order executive functions in adults. As stated previously, these cognitive processes undergo significant developmental changes across adolescence. Thus, since much of the research has used the PASAT to assess cognitive and executive functions in predominantly adult populations, its effectiveness in assessing adolescent cognitive maturation remains unclear. One of the purposes of this study was to more closely examine the utility of the PASAT for assessing developmental changes across adolescence as well as the important role of demographic factors such as relationships between age, IQ, and sex with executive functioning, by looking at performance on the PASAT in an adolescent population. An overarching goal of this study was to better understand the development of executive functions across adolescence, as well as to enhance our understanding of brain-behavior relationships during this important developmental period.

In the current study, I examined several predictor variables (age, IQ, and sex) of PASAT performance in a sample of 101 healthy adolescents. Much of the literature on the PASAT has demonstrated a need to control for specific variables, such as age (Brittain et al., 1991; Roman et al., 1991; Wiens et al., 1997) and intellectual ability (i.e., IQ [e.g., Brittain et al., 1991; Egan, 1988; Kanter, 1984; Roman et al., 1991; Sherman, et al., 1997; Wiens et al., 1997]), when interpreting results, as these factors have been shown to correlate significantly with PASAT performance. Thus, I hypothesized that age and IQ would significantly predict PASAT performance. Consistent with the adult PASAT literature, I also hypothesized that sex would not be a significant predictor of

PASAT performance, despite well-documented sex-based differences in neurodevelopment that exist during adolescence (e.g., De Bellis et al., 2001; Giedd et al., 1997; Lenroot et al., 2001; Reiss et al., 1996).

Results from stepwise multiple regression analyses indicated that the linear combination of age, IQ, and sex significantly predicted performance on the PASAT 3.0s and PASAT 2.0s. For both conditions, the combination of these predictor variables accounted for 34% of the variance in PASAT performance. For both PASAT 3.0s and PASAT 2.0s, age was the strongest predictor, with an increase in performance seen across adolescence. Thus, PASAT performance was better in older versus younger adolescents. IQ was the next strongest predictor variable, demonstrating a significant positive relationship between intellectual ability and PASAT performance. Adolescents with higher IQ scores achieved higher PASAT scores. Additionally, sex was found to be a significant predictor variable, with boys outperforming girls across both trials. This finding was unexpected, and contrary to our hypotheses that were based on prior PASAT literature. The boys in this sample had significantly higher average PASAT scores than the girls, and based on the results from the *t* test and Cohen's *d* statistic in the Results section, the difference in these two sample-means likely represents a genuine difference between the larger population of girls and boys that these samples represent.

Because all three independent variables, age, IQ, and sex, significantly predicted performance on the modified version of the PASAT, I wanted to ensure that the interaction effects of these variables were not better predictors of PASAT performance, above and beyond the main effects of age, IQ, and sex alone. Follow-up multiple regression analyses with age, sex, and their interaction (age-by-sex) indicated that the



linear combination of age and age-by-sex interaction significantly predicted performance on PASAT 3.0s, together accounting for 25% of the variance in PASAT 3.0s scores.

Although age was still the strongest predictor of PASAT 3.0s performance, the interaction effect of age-by-sex was also a significant predictor variable. These results suggest that older adolescents outperform younger adolescents on PASAT 3.0s, regardless of sex; however, older boys perform significantly better than younger boys and girls.

The linear combination of age and sex were significant predictors of PASAT 2.0s performance, and together accounted for 24% of the variance. Again, age was still the strongest predictor of PASAT 2.0s performance. However, boys as a group significantly outperformed the girls.

The linear combination of IQ-by-sex interaction and IQ significantly predicted performance on PASAT 3.0s and PASAT 2.0s, together accounting for 11%, and 14% of the variance in PASAT performance, respectively. A closer look at the regression coefficients showed that the IQ-by-sex interaction best predicted PASAT performance, above the main effects of IQ and sex alone. Inspection of the simple slope plots for these analyses revealed that the effect of intelligence on PASAT performance was greater for girls than for boys. Girls with lower intellectual ability scores had much lower PASAT performance than boys with similar IQ scores.

Unlike most of the literature involving adult populations, our findings suggest that sex is a very important, and significant predictor variable of PASAT performance in this adolescent sample. In a few studies with adults, males have been shown to perform slightly better than females, but the effect was not considered clinically meaningful

(Brittain et al., 1991; Wiens et al., 1997). In one large study of 560 healthy adults, gender accounted for less than 1% of the variance in PASAT scores (Diehr et al., 2003). Thus, this study raises the question as to possible explanations accounting for the pronounced sex effect in this study, as compared to most of the adult literature that indicates findings to the contrary. Could it be that this modified, adult version of the PASAT is sensitive in detecting an important sex-based difference in performance when used solely with adolescents, but not with adults or even younger children?

To look at this more closely, I further evaluated the literature on the CHIPASAT, the children's version of the PASAT (Johnson et al., 1988) to see if there was a pronounced sex effect in children. The CHIPASAT was created to assess attention and processing speed in children and adolescents. The CHIPASAT was normed on 315 individuals (167 girls) between the ages of 8 and 14.5 years of age. As noted previously, this version is less difficult than the adult version. When looking at the CHIPASAT literature, however, there is no reported sex effect on PASAT performance. If the literature on the PASAT and CHIPASAT suggest that sex is not an important predictor variable in PASAT performance, then why does this study indicate that it is a significant predictor variable? Could it be that, although both versions were created with the intention of assessing similar cognitive functions, they are actually sensitive to different functions? Or, are sex-based differences unique to the adolescent developmental period?

Adolescence is often described as a vulnerable developmental period characterized by the reorganization of structural and functional mechanisms responsible for the regulatory control of cognitive, emotional, and behavioral functioning. Because many of these systems mature at different rates, and are under the control of both

common and independent biological processes, adolescence is considered a critical time of considerable adjustment, “fraught with both risks and opportunities” (Steinberg, 2005, p. 69). Much of the brain development occurring during adolescence is in regions and systems of the brain critical to the regulation of behavior and emotion, and to the perception and evaluation of risk and reward. However, pubertal maturation responsible for changes in arousal, motivation, and affective response, often precedes the development of regulatory competence, thus creating a disjunction between an adolescent’s affective experience and his or her ability to regulate arousal and motivation. It is speculated that this disjunction between affective response and regulatory control, contributes to the emotional and behavioral dysregulation and overall volatility often seen during adolescence (Steinberg, 2005). Dahl (2001) likens these disjunctions to a situation in which one is starting an engine without yet having a skilled driver behind the wheel.

Because of the vast number of changes occurring during this developmental period, it is difficult to state with certainty the explanation for these robust sex-based findings. However, I can speculate that they may be attributable to important sex-based differences in a variety of areas, including differences in neurodevelopmental trajectories, cognitive abilities, pubertal development, and emotional functioning, which are unique to adolescence.

Much of the literature on adolescent brain development suggests that neurodevelopmental trajectories are significantly different between boys and girls (De Bellis et al., 2001; Lenroot et al., 2007). As discussed in the literature review, adolescent males have larger brain volumes than females (De Bellis et al., 2001; Giedd et al., 1997; Reiss et al., 1996), and reach their peak volumes later than females (14.5 years old versus

10.5 for females [Lenroot et al., 2001]). Regional gray matter volume in females tends to peak earlier than in males, whereas, white matter in males tends to grow more rapidly than in females (Perrin et al., 2008). Although many of the regional volumetric differences can be attributable to varying brain sizes, adolescent males have been shown to have more white matter volume in the frontal lobes, even after controlling for total brain size (Lenroot et al., 2007; Schmithorst et al., 2008). The prefrontal region of the brain is known to undergo considerable myelination during late childhood and early adulthood (Klingberg et al., 1999; Yakovlev & Lecours, 1967), and is implicated in higher order (executive) regulation of cognitive functions (Braver & Barch, 2002; Bunge et al., 2002; Demetriou et al., 2002; Goldman-Rakic & Leung, 2002; Huttenlocher, 1990; Levin et al., 1991; Luciana et al., 2005; Luna et al., 2004; Marsh et al., 2006). Many of these unique sex-based differences in neurodevelopment during adolescence are thought to underlie the differences in cognitive functioning between boys and girls (for review, see Marsh et al., 2008).

Sex-based differences in cognitive abilities have been well documented in the literature in adult samples (Marsh et al., 2008). Generally, males have been found to have better spatial abilities, outperforming females on tasks of mental rotation, spatial perception, and mathematical skills. Females, on the other hand, have been found to have better verbal skills, outperforming males on tasks of verbal fluency, manual speed, and verbal and item memory (Caplan, Crawford, Hyde, & Richardson, 1997; Collins & Kimura, 1997; Delgado & Prieto, 1996; Linn & Petersen, 1985; McGivern et al., 1997). As stated before, the PASAT has been shown to be a sensitive measure of multiple cognitive processes, including processing speed (De Luca et al., 1994; Demaree et al.,

1999; Madigan et al, 2000; Ponsford & Kinsella, 1992), sustained attention (Dyche & Johnson, 1991; Gronwall, 1986; Spreen & Strauss, 1998), auditory verbal working memory (Audoin et al., 2003; Christodoulou et al., 2001; Cicerone & Azulay, 2002; Di Stefano & Radanov, 1995; Dyche & Johnson, 1991; Litvan et al., 1988; Snyder & Cappelleri, 2001; Spreen & Strauss, 1998; Webbe & Ochs, 2003), and inhibitory control (O'Donnell et al., 1994; Spikman et al., 2001). Although the results of this study indicate that adolescent boys perform significantly better than adolescent girls on the PASAT, the complexity of this measure, and its requirement of the integration of several different cognitive processes makes it hard to determine exactly what is driving the significant findings. If I consider the literature, however, I am able to speculate that because adolescent males have more white matter volume in the frontal lobes than females (Lenroot et al., 2007; Schmithorst et al., 2008), and because increases in white matter volume are positively correlated with faster and more efficient speed of information processing (Changeux & Danchin, 1976; Huttenlocher, 1979; Yakovlev & Lecours, 1967), the adolescent males in this study have faster processing speed than the females, and thus, this cognitive strength accounts for the significant findings in this study.

While this hypothesis certainly seems consistent with the literature, another important consideration beyond the effects of speed of information processing and executive functioning is math ability. PASAT performance has also been shown to be affected by math ability (Chronicle & MacGregor, 1998; Gronwall & Wrightson, 1981; Hisock et al., 1998; Royan et al., 2004; Sampson, 1954; Sherman et al., 1997; Tombaugh et al., 2004). For example, Royan et al. (2004), and Tombaugh (2004) compared the performance of a group of adults on both versions of the PASAT, the PASAT (adult

version) and CHIPASAT, in order to determine which version was best predicted by math ability. Although performance did not differ, regression results indicated that scores on a math test accounted for a greater amount of variance in PASAT performance, than for the easier CHIPASAT. Although both measures were designed to assess similar cognitive functions (attention, working memory, inhibition, and processing speed), the researchers indicated that performance on the PASAT was more impacted by math ability. Therefore, to truly assess cognitive functions such as attention, working memory, inhibition, and processing speed, and to reduce the effects of math ability on performance outcome, the investigators recommended using the CHIPASAT in place of the PASAT. This information, coupled with the fact that there is no gender effect found in the CHIPASAT literature, made me question whether the prominent sex effect seen in this study could be attributable to important sex-based differences in math ability which are not necessarily present during childhood or adulthood. Despite the fact that adolescent boys have more white matter than adolescent girls, and that this is associated with faster processing speed, the fact that the adult version of the PASAT is more sensitive to math ability raises the question as to whether the significant findings in this sample were driven by a difference in math ability between boys and girls, rather than a difference in speed of information processing.

There has been an ongoing debate in the literature regarding the existence of gender differences in math abilities and achievement (Hyde et al., 1990; Kimball, 1989; Willingham & Cole, 1997; for reviews, see Gallagher & Kaufman, 2005; Geary, 1996; Halpern, 2000; Halpern et al., 2007; Hedges & Nowell, 1995). While a comprehensive meta-analysis using over 100 studies to investigate gender differences in math found little

difference existed in performance on several math tasks between the two sexes (Hyde et al., 1990), other studies suggest that males outperform females on standardized tasks of mathematical achievement (as reviewed in Gallagher & Kaufman, 2005) with these differences being noted in select groups of high achieving and gifted children and college students (Benbow et al., 2000; Hyde et al., 1990). Males have also been shown to outperform females on tasks of mathematical reasoning and geometry (as reviewed in Fennema, Sowder, & Carpenter, 1999) as well.

While it is certainly possible that sex-based differences in PASAT performance may be attributable to differences in actual math ability, there are also important sex-based sociocultural factors that are thought to influence an individual's attitude toward math, and their overall interest and engagement in math-related activities, which subsequently affects their motivation to develop and improve their math ability.

Research has found that, traditionally, parents tend to view math as being more important or appropriate for sons, while language arts and social studies are considered to be better suited for daughters (Andre, Wigham, Hendrickson, & Chambers, 1999). Parents are more likely to encourage sons to take advanced classes in mathematics and science and tend to have higher expectations for their success (as reviewed in Wigfield, Battle, Keller, & Eccles, 2002). The literature suggests that these belief systems that are so deeply engrained in many cultures worldwide, directly affect the development of a youth's perception of math, and impact his or her beliefs about the usefulness of mathematics. Not surprisingly, these belief systems also impact the sense of confidence one feels toward learning about mathematics as well, which has been identified as a strong predictor of math performance (Casey, Nuttall, & Pezaris, 2001).

These sociocultural influences that shape a child's perception of math not only exist in the home, but in the classroom as well. For example, girls are not as likely to engage in math classes because they are often overlooked by teachers, not encouraged to participate, or are too intimidated to engage for fear of looking inferior (Peterson & Fennema, 1985; Sadker, 1999; for review, see Sadker & Sadker, 2009). By the age of 12, girls begin to prefer language arts and social studies over mathematics (Sadker, 1999), and by high school, they often begin to self-select out of higher level math classes as they do not expect to do well in math classes and attribute this expectation of failure to lack of ability (Eccles, Barber Jozefowicz, Malenchuk, & Vida, 1999). Boys, on the other hand, tend to be much more supported in the classroom, and thus have been shown to display greater confidence in their math skills, which has been found to be a strong predictor of math performance (Casey, Nuttal, & Pezaris, 2001). Therefore, when speculating about what could actually explain significant findings in this study, although math ability may be responsible for the boys outperforming girls on the PASAT, important sociocultural factors and sex-based differences in perceptions and attitudes toward math-related activities could be contributing factors. Perhaps the girls in this study had more negative feelings associated with math-related activities, and thus weren't as motivated or inclined to fully engage in the PASAT. While this is purely speculation it brings to light important factors that could be influencing the sex-based differences seen in this study.

In addition to the important sex-based differences in neurodevelopmental trajectories, processing speed/executive functioning, and math ability and sociocultural factors that may be contributing to the sex-based differences in PASAT performance found in this study, it is also important to note the influence of pubertal processes and



differences in hormonal development between boys and girls during adolescence. Although a full review of this topic extends beyond the scope of this dissertation, research has shown that sex steroid exposure during puberty is associated with sex-specific organizational effects in the brain which continue well into adulthood (for review, see Sisk & Zehr, 2005). This sex steroid exposure is thought to have important cognitive and behavioral implications. Several studies have found that brain activation and cognitive performance fluctuate throughout the menstrual cycle, providing further support regarding the influence of sex-steroids on neuronal plasticity and cognitive functioning (Goldstein, 2006). Specifically, performance on tasks of spatial ability (Hausmann & Gunturkun, 2000; Schoning et al., 2007), semantic performance (Konrad et al., 2008), and learning and memory (for reviews, see Farage, Osborn, & Maclean, 2008; Sherwin, 2003) have been found to fluctuate with temporary changes to sex-steroid exposure during the menstrual cycle. A more recent study examining interhemispheric inhibition found that during the menses, the influence of the left hemisphere is much stronger, while lateralization decreases as estradiol hormones increase during the follicular phase (Weis et al., 2008).

Brain regions that demonstrate notable structural sexual dimorphism and that have a large number of sex steroid receptors include the basal ganglia and the limbic structures. For example, several imaging studies have shown that the caudate (Filipek et al., 1994; Giedd et al., 1997; Sowell et al., 2002; Wilke et al., 2007) and the hippocampus are proportionately larger in females, whereas the amygdala is larger in males (Giedd et al., 1997; Goldstein et al., 2001; Wilke et al., 2007). It is thought that greater densities of estrogen receptors in the hippocampus create heightened sensitivity to estrogen levels,

whereas greater densities of androgen receptors in the amygdala create a heightened sensitivity of this area to testosterone levels.

The fact that males have been found to have larger amygdalae than females is interesting in relation to these findings, because along with its involvement in the processing of emotional stimuli (as reviewed in Zald, 2003), the human amygdala has been found to modulate higher order cognitive functions, including working memory (as reviewed in Schaefer & Gray, 2007). Relevant to this study, research has found that amygdala activity (i.e., amplitude of *f*MRI BOLD response) is strongly correlated with response speed and accuracy on working memory tasks, and that this correlation becomes stronger with increased task difficulty and cognitive load (Schaefer et al., 2006). Therefore, individuals who demonstrated the highest magnitude of amygdala BOLD activity were those who responded the fastest on the most complex and cognitively demanding tasks of working memory. The investigators hypothesized that more challenging and difficult tasks or situations cause enhancement of the reactivity of the amygdala to task-and goal relevant stimuli. This enhanced amygdala response would then be projected to cognitive and/or motor systems, thereby facilitating adaptation to the challenging task or situation (David & Whalen, 2001; Schaefer et al., 2006).

Returning to the need to account for sex-based differences on the PASAT with the information that males have larger amygdalae than females in mind, I can speculate regarding the potential relationship between amygdala size and working memory function as related to PASAT performance. As discussed in their recent review, causality has not yet been established between normal variation of brain development and functional ability (Lenroot & Giedd, 2010). Thus, I can only wonder if there is a positive

relationship between amygdala size and working memory function, and if so, given that males have larger amygdalae, do they also have greater sensitivity for an enhanced amygdala reaction when exposed to the complex working memory tasks involved in the PASAT?

Some studies have suggested that the relationship between the amygdala and working memory is mediated by dopaminergic pathways, and that extracellular dopamine levels increase with task complexity and demand (Aalto, Bruck, Laine, Nagren, & Rinne, 2005; Fried et al., 2001). In relating this information back to this study, perhaps it can be hypothesized that if endogenous dopamine levels increase in relation to the difficulty of the working memory task, then there is likely a positive relationship between dopamine levels and working memory capacity. Therefore, males who have larger amygdalae, in turn have more dopamine receptor binding sites, and thus have the capacity to produce more dopamine. The thought here is that males may then have more dopamine reserved for use in higher order cognitive functioning, and thus will perform better than girls on complex tasks of working memory, like the PASAT. Again, this is only speculation, as the links between sex differences in brain structure, functional capacity, and behavior have yet to be determined (Lenroot & Giedd, 2010).

The literature regarding sex steroid receptors and structural sexual dimorphism is also interesting in terms of potential psychological implications. As stated above, adolescence is marked by a rather large disparity in rates of onset, course, and symptomatology of common psychiatric disorders between boys and girls (as reviewed in Lenroot & Giedd, 2010). Perhaps understanding how sex-steroid exposure and pubertal development affect vulnerability or resilience to specific neuropsychiatric disorders, as

well as the differences found in hormonal response to stress (Angold, Costello, & Worthman, 1998; McCormick & Mathews, 2007) could also help to elucidate what is driving these prominent sex-based findings. For example, as stated above, the caudate nucleus is relatively larger in female brains, and is dense in estrogen receptors. However, this nucleus has been implicated in ADHD and Tourette's Syndrome, which are both more common in males (Castellanos et al., 1996). Conversely, the amygdala, which is larger in males and dense with androgen receptors, has been implicated in affective disorders (depression and anxiety), which are more common in females (Drevets, 2000; for reviews, see Becker et al., 2007; McEwen, 2001; Romeo, Waters, & McEwen, 2004). Thus, taking this information one step further, perhaps smaller caudate nuclei and subsequently less estrogen receptors contribute to a biological predisposition males may have to developing certain psychiatric disorders such as ADHD and/or Tourette's. It has been suggested that the pubertal surge in estrogen levels seen in females (but not males) has a neuroprotective effect against schizophrenia in that it delays the onset of the disorder and ameliorates some of its effects (Kulkarni et al., 2008). In females, perhaps smaller amygdalae and subsequently less androgen receptors creates a biological vulnerability and heightened susceptibility in females to develop certain affective disorders. Studies indicate that the increase in incidence of depression in females is linked to an increased response of the HPA axis to stress with advancing puberty, and that in males, this response is decreased, potentially associated with increased testosterone levels (McCormick & Mathews, 2007).

While none of the participants in this study met criteria for a psychiatric disorder, this topic is briefly touched upon to address the fact that in addition to sex-based

differences in neurodevelopmental trajectories and neuroanatomy, which could very well be contributing to the cognitive differences seen between the boys and girls in this study, recent research highlights the importance of considering the influence of puberty and hormonal development on sex-based differences in cognitive and behavioral functioning seen across adolescence. As stated above, research has shown that sex steroid exposure during puberty is associated with sex-specific organizational effects in the brain, which are thought to have cognitive, behavioral, and psychiatric implications. Again, while none of my participants met criteria for a diagnosable psychiatric disorder, another important piece of information to address in this discussion is the potential for sex-based differences in acute stress reaction, and how these could possibly contribute to the cognitive differences seen in this study.

The PASAT has been described as a difficult, aversive, frustrating, and anxiety-provoking test (Aupperle et al., 2002; Diehr et al., 2003; Holdwick & Wingfeld, 1999; Hugenholtz, Stuss, Stethem, & Richard, 1988; Iverson, Lovell, & Smith). Participants in research studies who have been administered the PASAT have reported that they would rather have a lumbar puncture than have to take the PASAT again (Diehr et al., 2007). Research has shown that test administration induces a stress reaction in the form of both physiological arousal and psychological distress (Holdwick & Wingfeld, 1999; Lejuez et al., 2003). Many authors caution that the PASAT is not appropriate for individuals who are highly anxious, sensitive to fears of failing, or who are experiencing post-trauma distress (Kinsella, 1998; Roman et al., 1991) as it has been shown to cause anxiety, and to negatively affect mood and self-esteem (Holdwick & Wingfeld, 1999).

While the literature on sex-based differences in stress reactivity is somewhat inconsistent, a general trend has been established to suggest that males have greater HPA and autonomic response to psychological stressors than females (for reviews, see Kajantie & Phillips, 2006; Kudielka & Kirschbaum, 2005). However, females tend to have greater cortisol elevation than males when the stressor involves a social rejection task instead of a task of achievement (Dickerson & Kemeny, 2004; Stroud, Salovey, & Epel, 2002), as women are more likely to be negatively affected by interpersonal events than men (Ge, Lorenz, Conger, Elder, & Simons, 1994). A noticeable theory based on neuroendocrine and behavioral evidence posits that men display a *fight-or-flight* (Cannon, 1932) stress response that typically activates the sympathetic nervous system and the HPA axis, and invokes resources that increase focus, alertness, and fear (for reviews, see Kajantie & Phillips, 2006; McEwen, 2000). Several fMRI studies characterize this *fight-or-flight* stress response in males as an increase in cerebral blood flow and activation of the right prefrontal cortex, an important part of both the negative emotion and vigilance systems, with concurrent deactivation of the left orbitofrontal cortex, which is associated with positive emotion and hedonic goals (for review see, Kajantie & Phillips, 2006; Wang et al., 2005, 2007).

Females, on the other hand, demonstrate a *tend-and-befriend* stress response style (for review, see Taylor et al., 2000), which tends to build on attachment-care giving processes, especially those mediated by oxytocin that buffer sympathetic and HPA arousal (Blass, 1997; Chiodera et al., 1991; Field & Goldson, 1984). Oxytocin has been found to be positively correlated with relaxation and negatively correlated with interpersonal distress (Taylor, Klein, Greendale, & Seeman, 1999; Turner, Altemus,

Enos, Cooper, & McGuinness, 1999). From an evolutionary perspective, females respond to stress by nurturing their offspring, exhibiting behaviors that protect them from harm and reduce neuroendocrine responses that may compromise offspring health (i.e., quieting the offspring's cry [the tending pattern]), and by befriending or affiliating with social groups that maximize the survival of the species in response to stress during times of adversity (Taylor et al., 2000).

The female stress response is characterized by persistent activation of the limbic system, including the putamen, insula, cingulate cortex, and ventral striatum, the latter of which is considered a critical substrate of the human reward system and possesses rich receptors for oxytocin, vasopressin, dopamine, and endorphin (for review, see McClure, York, & Montague, 2004). Previous *fMRI* studies on social attachment have demonstrated activation in all of these areas in the female brain when addressing topics such as maternal and romantic love (Bartels & Zeki, 2000; Leibenluft, Gobbini, Harrison, & Haxby, 2004). Therefore, it is thought that the activation of these limbic areas may serve as an intrinsic neurobiological reward system under stress, and thereby down-regulate the *fight-or-flight* response, thus resulting in a blunted acute stress response. In addition, the anterior cingulate has been implicated in the attentional processing of emotion, self-assessment of one's mental state, empathy, and social exclusion (Davis, Taylor, Crawley, Wood, & Mikulis, 1997; Davidson & Irwin, 1999; Frith & Frith, 1999). Therefore, the persistent cingulate activation observed in the female brain following a stressful event is thought to reflect a greater degree of emotional 'rewinding' or melancholy thinking, which supports the female tendency to engage in ruminative thinking, or repetitively focusing on symptoms of distress and their possible causes and

consequences, when under stress (Butler & Nolen-Hoeksema, 1994; Papadakis, Prince, Jones, & Strauman, 2006).

Based on the preceding discussion, males and females respond differently to stressful events. While males invoke biological resources that increase focus, alertness, and fear in order to immediately react by either confronting the stressful stimuli or fleeing, females tend to have a biologically blunted acute stress response, which drives them to strengthen interpersonal bonds in order to manage stressful situations, as well as engage in self-assessing, ruminative thinking. Because the PASAT has been identified as such a stressful task, and has been found to induce a stress reaction in the form of both physiological arousal and psychological distress, perhaps the sex-based differences in acute stress response between females and males is one explanation for the results of this study. The PASAT is contraindicated for individuals who are afraid to fail. Because the female stress response is highly connected to social attachment and fears of rejection, perhaps the girls in this study were biologically predisposed to experiencing a heightened stress response to the PASAT, and thus did worse overall when compared to their male counterparts.

Along the same lines, perhaps as a result of a heightened stress response to the PASAT, the girls in this study engaged in more ruminative thinking, and subsequently had less cognitive resources available to allocate toward the very complex and cognitively demanding PASAT. Rumination is often associated with anxiety, depression, and other negative mood states (as reviewed in Nolen-Hoeksema, Wisco, & Lyubomirsky, 2008), and is known to contribute to difficulties with attention and concentration, executive functioning, and processing speed by occupying cognitive and



executive resources that would normally be allocated for these cognitive functions (Davis & Nolen-Hoeksema, 2000; Watkins & Brown, 2002). It is very likely that in this study, girls experienced the PASAT to be more stressful than boys, and as a result, engaged in more distracting ruminative thinking, and thus did more poorly overall than boys.

### **Limitations**

The present study has several limitations. First, due to the limited demographic variability of our sample, the generalizability of the results of this study to adolescents across diverse national, ethnic, and sociocultural backgrounds is limited. Specifically, this adolescent sample was recruited from a metropolitan area in the Pacific Northwest, and consisted predominantly of bright, high functioning, Caucasian adolescents from middle to upper class socioeconomic statuses. Although this sample clearly represents an important group of Pacific Northwestern adolescents, it is not representative of all adolescents. Therefore, a study examining PASAT performance in adolescent samples from multiple regions would be helpful to see if these results can be replicated across racially, ethnically, and socioeconomically diverse groups.

The PASAT has been identified as an incredibly anxiety provoking and frustrating test. Research has shown that a notable practice effect exists between the first and second trials. With repeated exposure, the novelty and subsequent anxiety has been shown to diminish substantially, and as a result, participants are more comfortable and better able to perform on this task. The presence of this practice effect raises the question of whether or not the first trial of the PASAT is an accurate measure of true ability. The literature suggests that the first trial is a better reflection of an individual's heightened emotional response to the PASAT, and it should be used as an additional practice trial.

Because only two trials were used in this study, the easier 3-second trial, and the more difficult two-second trial, the research design did not control for potential practice effects. Therefore, it is likely that results on the three-second trial were confounded by a stress response to the task, and may not actually be an accurate estimate of this sample's true ability. Thus, in the future it would be helpful to add an additional three-second trial to the beginning of the PASAT administration in order to compare results from both three-second trials, and to better control for potential practice effects. As stated earlier, adolescence is marked by emotional volatility, which is often due to the disjunction between an adolescent's affective response and regulatory control. Thus, adolescents tend to be reactive and disinhibited in their emotional responses. When confronted with a very stressful task like the PASAT, it is likely adolescents, similar to adults, experience frustration and become emotionally overwhelmed. However, unlike adults, adolescents do not possess the capacity to regulate this emotional response, and therefore are more susceptible to becoming overwhelmed by it. As a result, adolescents could easily become more distractable or unmotivated to continue participating in the task. As stated above, there are prominent sex-based differences in stress response between males and females, which could very well be contributing to our findings. Thus, by adding another practice trial to the research design, the intention would be to normalize the experience of the PASAT and reduce overall stress levels associated with the task. This would potentially reduce the effects of sex-based stress responses on the findings.

Additionally, despite this being a study focused on the developmental processes that take place during adolescence, the cross-sectional design of the current study only includes data collection at a single point in time. Thus, continuing to follow each participant

in a longitudinal fashion would allow us to capture within-subject changes and developments in PASAT performance along with brain related changes over time. This would improve my ability to make inferences unique to the developmental process while decreasing the natural confounds of inter-subject variability.

Another potential limitation of this study was the use of IQ as a predictor variable. Although much research has used IQ as a demographic predictor variable of PASAT performance, Diehr, Heaton, Miller, and Grant (1998) discourage this practice, and suggest using education level instead. They indicate that the use of IQ as a demographic predictor variable is problematic when using the normative data with a clinical population, as IQ is altered by many clinical conditions, many of which impact PASAT performance as well. Thus, using IQ-based PASAT norms would reduce the chances of detecting disease-related changes in PASAT performance. Instead, these investigators believe that ethnicity and education are likely to be much better predictor variables of PASAT performance, as they are constant throughout the lifespan, and are not vulnerable to disease processes. Although this seems to make sense, much of the literature has found the contrary, in that education and ethnicity are not in fact significant predictors of PASAT performance. However, these investigators have argued that this is due to a design flaw in that many studies assessed the impact of these variables while covarying for IQ at the same time. Because IQ is so highly correlated with both of these demographic variables (ethnicity/education level) in adult samples, it reduces the potential main effect of each individual variable. Thus, using predictor variables that are less related would provide a better understanding of the unique contribution of each predictor variable to PASAT performance. In the case of this study, correlation

coefficients were computed to see if any of the predictor variables (age, sex, and IQ) were significantly related to one another. Results indicated that none of my predictor variables were significantly related to one another.

The arguments put forth by Diehr et al. (1998) related to the use of education level and ethnicity instead of IQ are less relevant for the current study as most of the adolescents did not vary in education level beyond age-related differences in grade level. Further, the mean IQ level in this study was higher than would be found in a general community sample. It is likely that the higher intellectual ability scores in this sample may have affected the results by truncating the relationship between IQ and PASAT performance.

Further, there was also limited ethnic variability for this sample. However, to confirm that education and ethnicity were not better predictors than IQ, as an additional exploratory analysis, I reran our regression analyses, and replaced IQ with education level and ethnicity to see if these variables were in fact better predictors of PASAT performance in this adolescent sample. For both PASAT 3.0s and PASAT 2.0s, ethnicity and education level were excluded from the final models, as age and sex accounted for most of the variance in PASAT performance. This could very well be due to the limited ethnic diversity of the sample, as well as the truncated span of years of education that ranged from 5<sup>th</sup> to 11<sup>th</sup> grade. These variables may be important considerations in diverse adult samples when there is greater variation in both ethnicity and education level.

### **Implications and Recommendations for Future Research**

The findings from this study contribute to the literature on the PASAT, as well as to knowledge of the development of executive functions across adolescence. There are

several implications of the present results. In this study, I found that this modified adult version of the PASAT is sensitive to the effects of age and intelligence, as well as sex. Although much of the literature on the PASAT supports the idea that age and intelligence are contributing factors to performance on this task, the idea that sex plays such a strong role in how adolescents perform on the PASAT is relatively novel. The pronounced sex-effect found in this study bodes the question, why are clinicians not controlling for sex when assessing, scoring, and interpreting data on executive functioning in adolescent populations? Looking at many of the comprehensive executive functioning batteries that exist (e.g., Delis Kaplan Executive Function System, 2001), these assessments do not control for variables such as intelligence, and do not provide separate norms for males and females as might be found for social-emotional and behavioral measures used with adolescents (i.e., the Youth Self-Report, 1991; YSR). If the results from this study are generalizable to the larger population of adolescents as a whole, it seems researchers and clinicians are in absolute need of normative data that take into account these variables when assessing individuals from this developmental period.

In addition, although the PASAT is one of the oldest, and most widely used neuropsychological assessments on the market, its applicability in assessing adolescent cognitive functioning has been limited. Although much effort has been expended over the years to create new and improved, more sensitive measures of the PASAT to assess adult populations, and although a completely separate test was constructed to better serve young child populations, no version specific to an adolescent population exists. What is amazing about this fact is that adolescence has been identified as a developmental period characterized by marked changes in higher order cognitive functioning, yet one of the

most sensitive measures available on the market is not truly designed to assess this particular population. In this study, the adult version of the PASAT was very sensitive in detecting important developmental processes that occur during adolescence. This is seen in the graphic depictions of my results (Figure 1), as it shows good range and lacks a ceiling/floor effect when used with this age group. While there are many advantages to using the adult version of the PASAT with an adolescent population, this study does highlight the need for researchers to take a closer look at adolescence as its own unique developmental period, and refine the assessment measures used in order to account for important sex-based differences in cognitive and behavioral functioning, and neurodevelopmental trajectories. Due to the distinct sex-based differences in neurodevelopment, hormonal/pubertal development, and cognitive and emotional functioning seen across this critical period, it is imperative that assessment tools are available that are not only sensitive to capturing the multitude of maturational processes, but that can address these sex-based differences in performance. Pertaining to this study, because boys significantly outperformed girls on both trials of the PASAT, it would be helpful to have access to gender-based normative data to account for the significant sex-based differences seen in performance on this task.

Although I can speculate as to what is driving the profound sex-based differences in PASAT performance found in this study, these results simply emphasize the need for more research on adolescent brain development, and more specifically, on brain-behavior relationships. Due to the changes occurring during adolescence, including the biological, physiological, neurological, hormonal, cognitive, behavioral, psychological, and socioemotional changes, it is difficult to directly link specific behaviors with particular

biological processes. However, with the rapid advancements in magnetic resonance imaging technology, the ability to assess these relationships and truly understand the underlying mechanisms subserving changes in adolescence can become a greater reality.

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